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Evaluating the Feasibility of Systematic Inland Water Quality Monitoring with Satellite Remote Sensing

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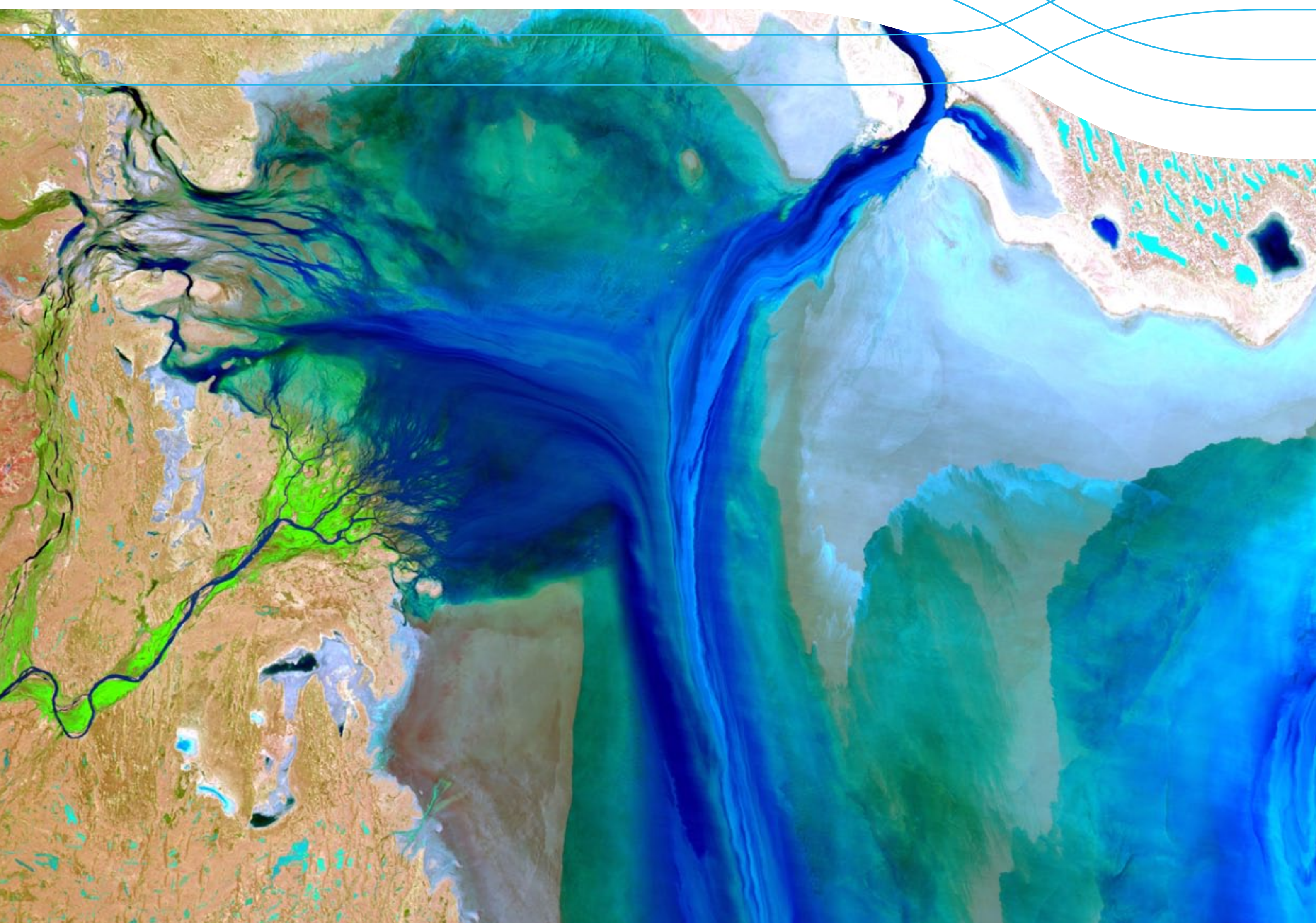

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Cover photograph

Landsat TM image of Lake Eyre on March 28, 2011. Courtesy of Geoscience Australia. Water is remarkably photogenic. This image was created using the amazing ability of water to transmit, disperse and reflect light in ever changing patterns of colour as seen from space by the Landsat satellite.

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Executive summary

Water quality is a fundamental aspect of Australia's freshwater resources. Information about water quality is needed to assess baseline conditions and to understand trends for water resource management. The Bureau of Meteorology has an ongoing interest in water quality monitoring in response to its responsibilities under the *Water Act 2007* and the *Water Regulations 2008*. However, existing water quality information coverage is limited in its geographic and temporal coverage and accessibility.

This report examines the feasibility, resource requirements and potential of remote sensing from satellites (earth observation) for developing an Australian inland water quality monitoring capability. The project was initiated by the National Plan for Environmental Information (NPEI) with an aim to provide improved information for Australia's National Water Quality Assessment (NWQA) The report also has broader relevance, for example for supporting State of the Environment (SoE) reporting under the *EPBC Act*.

Based on the policy, legislative and environmental drivers, there is a strong case for investing in operationalisation of a national inland water quality monitoring program. This is because existing water quality information is sparse, difficult to obtain, and variable in content and accuracy. Earth observation for water quality monitoring is well suited for Australia's large areas with sparse population and limited access. The state of the science is sufficiently advanced to produce earth observation-based water quality information at multiple spatial scales and temporal frequencies for both current and historic conditions back to 1984.

This report recommends a top-down hierarchical monitoring program that aligns with the NWQA and SoE reporting frameworks. A framework for this program would include:

- Low spatial high temporal resolution earth observation sensors that provide national level reporting. These will enable monitoring of 2,300 water bodies in Australia, representing 2% of the total water bodies on the continent and 11% of the total inland water surface area.
- Medium spatial and temporal resolution earth observations sensors that provide regional, state and river basin reporting. These sensors enable monitoring of 63,000 water bodies in Australia, representing 42% of the total water bodies on the continent and 32% of the inland water surface area.
- High spatial resolution sensors that are suitable for detailed reporting based on regional and local water management agency needs.

The initial earth observation-derived water quality variables for a national monitoring program are chlorophyll as indicator for trophic status, coloured dissolved organic matter to assess aquatic carbon content, total suspended matter and the light environment of the water column.

This information can be used to establish environmental baselines as well as for monitoring temporal and spatial change at local to national scales. However, the temporal frequency is limited by satellite overpass frequency and may be biased by cloud cover. The most readily available sensors for operationalisation of national scale monitoring, MODIS/MERIS and Landsat have limited ability to resolve small water bodies such as narrow river channels.

The recent and anticipated launch of new sensors and data streams, including the Visible Infrared Imagery Radiometer Suite (VIIRS), the Ocean Land Colour Instrument onboard Sentinel 3, and the Landsat Data Continuity Mission ensure that investments in operationalising an earth observation-based monitoring program will have long lasting impact.

The greatest impediment for operationalisation of earth observation for inland water quality monitoring is the lack of bio-optical information on Australia's inland water bodies for parameterisation and validation of water quality information.

Part I Inland Water Quality Monitoring

1 Introduction

Water quality is a fundamental aspect of Australia's freshwater resources. Important to human consumption, agriculture, fishing and recreation, water quality is also a driver of Australia's aquatic ecosystems health. Information about Australia's water quality is needed to assess baseline conditions and understand trends for water resource management. However, existing water quality information coverage across the country is limited (SOE, 2011).

Satellite remote sensing has been suggested as a potential technological solution to this information gap because it can provide measurements over a wide area at regular intervals. The advent of new operational satellite sensors and supporting infrastructure provides new opportunities for developing remote sensing-based operational monitoring capabilities for Australia. Yet advances in the use of remote sensing for monitoring water quality are largely restricted to the research domain. There is limited understanding of the operational feasibility of remote sensing-based inland water quality monitoring and the resources needed to progress research to operational systems.

1.1 Water quality monitoring

Water quality monitoring is the systematic collection and analysis of samples with the aim of providing information and knowledge about a body of water. Monitoring of water quality (both surface and sub-surface) is undertaken for a range of reasons including protecting public health and aquatic ecosystems, environmental reporting, licence compliance and research. In Australia water quality monitoring is carried out by a wide range of organizations from state and territory agencies, catchment management authorities and local governments, private utilities such as drink water, agricultural and industrial water providers, and mining companies for privately owned waters and affected public waters.

1.2 Remote sensing and earth observation

Remote sensing measures energy reflected and emitted by the earth surface. Because different materials interact differently with photons at different wavelengths, it is possible to measure the composition of the Earth surface using the principles of spectroscopy. Remote sensing makes it possible to collect data in inaccessible or dangerous locations.

Earth observation is the term used to refer to remote sensing measurements made from aircraft or satellites. These observations are often collected in a two-dimensional array of pixels. Multiple two-dimensional arrays of pixels recorded at different wavelengths (bands) comprise a digital image. Thus, an earth observation image may contain both spatial and spectral information of the earth's surface, providing a wealth of information for environmental science and monitoring.

REMOTE SENSING: measuring the earth's surface without coming into contact with it through sensing and recording reflected or emitted energy.

EARTH OBSERVATION: remote sensing measurements made from aircraft or satellites.

As remote sensing and earth observation are often used interchangeably, we reserve the term earth observation for reflected and emitted optical (visible, near and thermal infrared regions) energy measurements made from aircraft or satellites, whilst the term remote sensing pertains to all reflected and emitted energy measurements where there is a distance between a sensor and the object or material measured. Earth observation always has a spatial component and always provides a snapshot (image) in time. For this report we exclude point and line sensors from aircraft or satellites. Remote sensing encompasses boat, jetty or other platform based measurements of reflected or emitted energy in the visible, infrared or thermal regions.

1.3 The role of earth observation in water quality monitoring

Earth observation has the potential to provide spatially and temporally comprehensive information on a limited set of water quality variables, derived from reflectance information in the visible, near infrared and thermal infrared wavelength regions.

Optical remote sensing measures solar radiation reflected from the earth's surface across the optical portions of the electromagnetic spectrum (visible, near and shortwave infrared wavelength regions). Because different aquatic materials such as suspended matter, chlorophyll pigments in phytoplankton, and bottom sediment interact differently with photons at different wavelengths, it is possible to detect the composition of water column constituents and, if visible, the substratum. Indeed, using an understanding of the interaction of different wavelengths of light with different materials (spectroscopy) is a fundamental method of many environmental measurements and traditional water quality monitoring techniques. By performing these measurements from spacecraft or aircraft, synoptic measurements are possible.

Earth observation can be used to establish environmental baselines as well as for understanding temporal changes. Environmental change detection can show temporal change (days to decades) and spatial change (0.4m to 1 km spatial resolution) at local to global scales. It can be used for analysing processes such as hydrodynamics, eutrophication, carbon flows, and changes in biodiversity. Earth observation has the potential for retrospective processing of archival images going back several decades.

1.3.1 WATER QUALITY VARIABLES THAT REMOTE SENSING CAN DETECT

In order to provide context to the following chapters it is necessary to briefly describe the water quality variables that can be measured directly from remote sensing and those that can only be derived indirectly. Appendix B provides a comprehensive primer on remote sensing of inland waters. Readers are referred to the glossary for more complete definitions of technical terms.

For the purposes of this report, inland waters are defined as dams, rivers, lakes, reservoirs and estuaries. Published methods using existing satellite and airborne sensors exist for assessing the surface water concentrations of:

- *Chlorophyll* (CHL): an indicator of phytoplankton biomass, trophic and nutrient status; the most widely used index of water quality and nutrient status globally.
- *Cyano-phycocyanin* (CPC) and *cyano-phycoerythrin* (CPE): indicators of cyanobacterial biomass common in harmful and toxic algal blooms.
- *Coloured dissolved organic matter* (CDOM): the optically measureable component of dissolved organic matter in the water column sometimes used as an indicator of organic matter and aquatic carbon.
- *Total suspended matter* (TSM) and *non-algal particulate matter* (NAP): important for assessing the quality of drinking water and controlling the light environment of aquatic environments.

Additionally, the following conditions can also be estimated:

- *Vertical light attenuation* (K_d) and *turbidity*: measurements of the underwater light field that are important to assessing the degree of light limitation, rates of primary production, species composition and other ecosystem responses.
- *Emergent* and *submerged macrophytes:* down to depth of visibility, important indicators of wetland and aquatic ecosystem health and function.
- *Bathymetry:* if the bottom or bottom cover of a water body reflects a measureable amount of light through the water column to above the surface then the water depth can be estimated.

1.4 The National Plan for Environmental Information (NPEI) initiative

The National Plan for Environmental Information (NPEI) is the first step towards a long-term commitment to reform Australia's environmental information base and build critical infrastructure for the future. The initiative is jointly delivered by the Bureau of Meteorology and the Department of Sustainability, Environment, Water, Population and Communities (SEWPaC). The Bureau's role is primarily technical. Key Bureau activities under the initiative are the development of an environmental information infrastructure, demonstrator products and services to establish foundation capability and a targeted environmental data review. A joint activity under NPEI is to determine the Australian government's priority requirements for environmental information.

1.4.1 THE NPEI PROJECT 'INLAND WATER QUALITY MONITORING WITH SYNOPTIC REMOTE SENSING'

The NPEI 'Inland Water Quality Monitoring with Synoptic Remote Sensing' project has been initiated for two key reasons.

1. In an initial scan of environmental information priorities, the National Plan for Environmental Information initiative identified a need for improved information regarding inland water quality.
2. The Bureau has an ongoing interest in inland water quality monitoring in response to its responsibilities under the *Water Regulations 2008* (page 122). However, to date the Bureau's ability to report on water quality has been limited.

The Bureau has a limited understanding of resource requirements and technical and applied feasibility for maintaining an operational capability for water quality monitoring using remote sensing. The aim of this report is to provide the Bureau with an evaluation of the feasibility of developing an operational inland water quality monitoring system for Australia. Specifically, this report addresses:

- The applied feasibility of monitoring inland (estuarine and freshwater) water quality with remote sensing: what can we monitor, where, how often, and when?
- The parameters for an operational system including satellite platforms, resolution, and costs associated with satellite data acquisition and processing.
- The current state of the knowledge and technology, with special attention to the limitations and research and development gaps in satellite-based inland water quality monitoring. This is illustrated by the conclusions drawn from six case studies conducted across a range of inland water bodies across Australia.
- Resource requirements for developing an operational system for Australia.

The anticipated outcome of this report is an improved ability for the Bureau to make informed decisions about developing and deploying an operational national inland water quality monitoring system.

To this end, CSIRO has conducted a thorough evaluation of the feasibility of systematic inland water quality monitoring with satellite earth observation. This report will cover:

1. The national and international context for inland water quality monitoring with earth observation. Specifically addressed are the national policy and program drivers for a national monitoring system, including the major drivers the National Water Quality Management Strategy and the *Water Act 2007* and *Water Regulations 2008*. This section identifies gaps and opportunities that may be addressed by an earth observation monitoring system.
2. Operational methods for inland water quality monitoring, including a summary of sampling considerations and an evaluation of existing monitoring methods. Readers are directed to chapter 3 for key summaries about the technical aspects of operational water quality monitoring.
3. The assessment of the feasibility of earth observation for water quality monitoring is elaborated upon in detail through six case studies. These case studies underpin the feasibility assessment of this report, conducted across a range of inland water bodies. They include:

- Queensland catchment-to-coast system: the Burdekin Falls Dam-Burdekin River-Great Barrier Reef lagoon
- lower Murray system: the River Murray from the New South Wales border to Coorong
- upper Murray system: the Murrumbidgee River lakes and reservoirs
- extreme events in the Murray system: the January 2011 Victoria black water flood event
- the ephemeral salt lakes of the interior: the Lake Eyre Basin rivers and lakes
- managed recreational lakes: Lake Burley Griffin in the Australian Capital Territory.

These six case studies provide useful information covering the issues relevant to the feasibility of satellite remote sensing such as spatial, spectral and temporal resolution, spatial coverage, and water quality products. Further, the six case studies demonstrate the current state of the science for inland water quality measurements from earth observation.

4. Project scoping for an operational inland water quality monitoring program from earth observation. To gather information to scope the operationalisation of a systematic monitoring program, the authors of this report conducted an online poll followed by a workshop that included a roundtable discussion by experts in operational remote sensing monitoring programs. The authors solicited expert opinions from members of the WIRADA collaboration, CSIRO, the University of Queensland and Geoscience Australia.

   Chapter 5 provides critical material to the NPEI team, presenting an assessment of the level of operation of satellite earth observation for inland water quality monitoring. Included in this section are the status and resource requirements for different operationalisation scenarios.

5. Conclusions and recommendations for developing and deploying an operational earth observation - based inland water quality monitoring system.

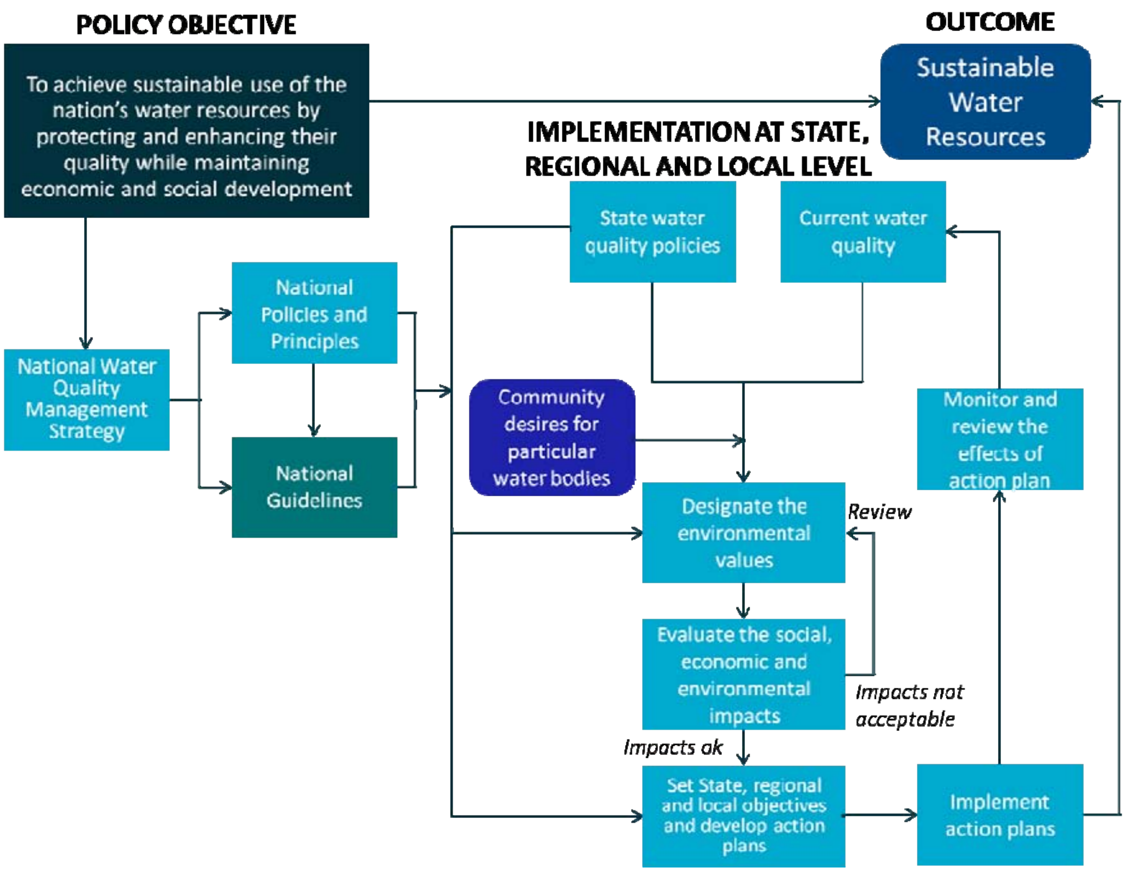
2 National and International Context

2.1 Policy and program drivers

There are several national policies and programs that require the type of water quality information that would be collected by a national water quality monitoring system. Major policy and program drivers include the National Water Quality Management Strategy (NWQMS), the National Water Initiative (NWI), the Australian Water Resources Assessment (AWRA), the State of the Environment (SoE) Reporting and the National Climate Adaptation Framework.

2.1.1 THE NATIONAL WATER QUALITY MANAGEMENT STRATEGY

The National Water Quality Management Strategy (NWQMS) is the primary water quality management apparatus in Australia, overseen by the Natural Resource Management Ministerial Council (NRMMC) and the Environment Protection and Heritage Council and implemented by state and territory governments. The policy objective is “to achieve sustainable use of the nation’s water resources by protecting and enhancing their water quality while maintaining economic and social development” (NWQMS, 1994). Figure 1 provides an overview of the NWQMS.



Source: http://www.environment.gov.au/water/publications/quality/pubs/nwqms-outline-of-policies.pdf

Figure 2-1 The National Water Quality Management Strategy

The NWQMS provides guidelines for Australia's water quality management. Specifically, the NWQMS provides:

- Implementation guidelines (NWQMS, 1998) and water quality targets (EnvironmentAustralia, 2002). The underlying principle is that water quality should be managed at a catchment level, using community environmental values for guiding local water quality targets. The targets are established by the governments in partnership with the community.
- Guidelines for fresh and marine water quality. The Australian and New Zealand Environment Conservation Council (ANZECC) guidelines on fresh and marine water quality form the central technical reference for the NWQMS (ANZECC, 2000). They provide numerical concentration limits or narrative statements for water quality for a wide range of ecosystem types and water resources uses.
- A framework for fresh and marine water quality monitoring and reporting in Australia (ANZECC, 2000), which notes the importance of water quality monitoring for fair management of water resources, detection and control of contaminants, assessment of environmental protection policies, and the development of water quality guidelines and standards. However, it is not intended to be a prescriptive document. Rather, it provides guidance for monitoring objectives, monitoring study design and effective sampling, laboratory analyses, and reporting of results and conclusions (ANZECC, 2000). Notably, the framework recommends that monitoring program design be iterative, based on best monitoring practice approaches. The framework anticipates continual updates as the state of the science and technology evolve.

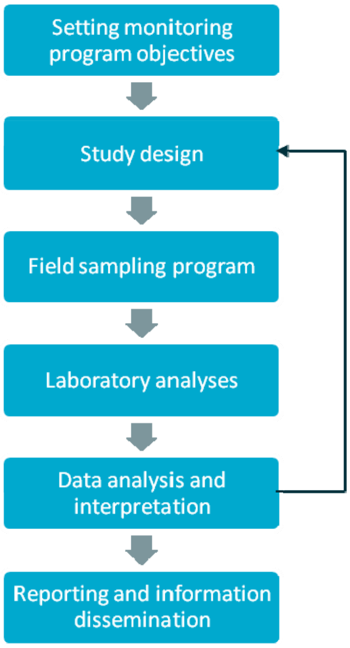


Figure 2-2 NWQMS framework for a water quality monitoring program

Source: **http://www.environment.gov.au/water/publications/quality/pubs/nwqms-monitoring-reporting-summary.pdf**

2.1.2 THE NATIONAL WATER INITIATIVE

The National Water Commission's (NWC) National Water Initiative (NWI) is a commitment by Australia's state and territory governments to achieve a "nationally compatible, market regulatory and planning based system of managing surface and groundwater resources for rural and urban use that optimizes economic, social and environmental outcomes" (NWI, 2004). Although primarily tasked with reforming Australian water allocations, water quality is considered an important component of Australian water resource management and water resource reform.

2.1.3 AUSTRALIAN WATER RESOURCES ASSESSMENT

The Bureau of Meteorology has an ongoing interest in inland water quality monitoring in response to its responsibilities under the *Water Regulations 2008* which are founded on the *Water Act 2007*, wherein the Bureau has a statutory responsibility to provide regular reports on the status of Australia's water resources and how they are used. The purpose of the Australian Water Resources Assessment (AWRA) reporting is to inform public policy and program development. It is intended to guide and provide focus for research and assist in assessing the performance of public water policies and practices. It also provides scientifically robust analysis and interpretation of changes in Australia's water availability, quality and use with the intention of consistent reporting across the nation and over time. This will enable spatial and temporal comparisons that result in enhanced understanding of Australia's water resources unconstrained by jurisdictional boundaries though on-line access to regular and ongoing reporting of water information.

AWRA reports will be regularly published and made freely available by the Bureau from 2011.The reports will provide information on Australia's water resources and show changes in water availability, quality and use. AWRA reporting will (ARWA, 2010):

1. Highlight patterns, trends and variability in water quantity and quality at local to national scales over time scales of months to decades.
2. Monitor water flows and stores and publish statistics for key reference sites.
3. Provide analysis outputs as maps, graphs, figures and tables.

It is likely that AWRA reports will be used for the State of the Environment reporting on inland water quality and condition.

2.1.4 AUSTRALIAN STATE OF THE ENVIRONMENT REPORTING

Under the *Environment Protection and Biodiversity Conservation Act 1999*, the Minister of SEWPaC is required to report to Parliament every five years on the state of the Australian environment. The State of the Environment (SoE) reporting objectives are to:

- Capture critical information about environmental issues that are nationally significant and of interest to current and future generations.
- Provide relevant and useful information on the state of the environment to support decisions about environmental policies and management at national and regional scales.
- Provide public access to accurate, up to date information on the state of the Australian environment.

Broadly defined under the Act, “the environment” assessed during SoE reporting includes a wide range of biophysical and ecological elements of the environment, as well as social and cultural aspects of environmental issues. Specifically, reporting on the environment includes:

- The current environmental condition
- The pressures on the environment and the drivers of those pressures
- Management initiatives to address environmental concerns and the impacts of those initiatives

SoE reporting occurs at two governmental levels in Australia: the Commonwealth level and the state and territory level. At the Commonwealth level, reporting occurs once every 5 years in a cycle of 1996-2001-2006-2011, etc. At the state and territory level the frequency and timing of the reporting are variable. The content of the SoE reports cover similar areas of interest, however there is little coordination between the Commonwealth and the states.

Inland water quality assessments for the past three SoE reports (2001, 2006 and 2011) have varied significantly. The 2006 SoE Inland Water section has three main subjects: water availability and use, assessments of river health, and investments in inland waters (SOE, 2006). On the other hand, the 2011 report focuses on salinity, nutrients, turbidity, pH, algal blooms and faecal contamination (SOE, 2011). The disparate approaches across SoE reports were likely due to the Commonwealth and the states being confronted with yearly to decadal climatic extremes in water quantity that caused the focus of the reporting to change.

2.1.5 CLIMATE CHANGE IN AUSTRALIA

"Climate change will present major water resource management challenges given Australia is a naturally dry continent and it has a growing demand for water. Climate change projections indicate that we can expect increased temperatures, reduced rainfall across eastern and far south west Australia, increased rainfall variability and evaporation as well as significantly increased frequency and severity of drought. Changes in the frequency of extreme weather events, including flooding are also anticipated.

Climate change is likely to increase the stress on rivers already under pressure from salinity, over-allocation and declining water quality. Higher water temperatures and reduced stream flows will adversely affect water quality affecting human uses and environmental conditions.

Drought conditions are likely to exacerbate erosion and downstream sedimentation. Higher sediment loads enter rivers following extreme rainfall events or extreme bushfire events, both of which are projected to increase with climate change.

Changed climatic conditions are also likely to produce conditions that favour riparian and aquatic weeds and algal blooms."

(Healey, 2009) Fast Facts, Water Management, Vol. 288. Spinney Press.

In 2010 water was named as one of six national priorities for climate adaption action by the Australian government. Under the National Adaptation Framework, agreed upon by the Council of Australian Governments (COAG) in 2007, a priority action is to reduce vulnerability of water resources to climate change (COAG, 2007).

The Department of Climate Change and Energy Efficiency provides recommendations for best practice regional natural resource management. Included in those recommendations are adaption options designed to alleviate existing pressures on vulnerable Australian ecosystems. Recommendations include improving water quality to reduce local stress on Australian landscapes (http://www.climatechange.gov.au/~/media/publications/adaptation/managing-australian-landscapes.pdf). Water quality monitoring information will be needed to support improvement actions.

2.2 Potential program users

In addition to the above major drivers for a national water quality monitoring program, there are many other actual and potential users of national water quality monitoring information. Some of these include:

- Caring for our Country program has a specific target for investment in the protection and improvement of coastal environments and critical aquatic habitats.
- The National Reserve System strategy through 2030 includes a complementary strategy toward improved marine and freshwater habitat and water quality.
- The Threatened Ecological Community managers under the *Environment Protection and Biodiversity Conservation Act 1999* need information relevant to characterizing key habitat variables (such as water quality) as well as processes threatening to candidate and nominated species.
- The Murray Darling Basin Commission must periodically assess and report on the water quality of the River Murray in order to effectively guide management actions along the river and its tributaries. Under the *Water Act 2007* clause 45, the MDBA must establish, maintain and operate consistent protocols for the collection and monitoring of river and tributary quality (WaterAct, 2007).

2.3 Regulatory requirements and indicators

The *Water Act 2007* and the *Water Regulations 2008* implemented key water management reforms in Australia, such as giving the Bureau water information functions for the nation.

Under the *Water Act 2007* the Bureau is required to collect, hold, manage, interpret and disseminate information on Australia's water. The *Water Regulations 2008* requires all individuals, trusts companies, corporations, and agencies of state, territory or Australian governments to give water information, including water quality information, to the Bureau. Table 2-3 shows the categories of organizations that are required to provide information to the Bureau (WaterRegulations, 2008). Categories likely to collect water quality information are in light blue. Categories less likely to collect water quality information are in dark blue.

Source: Water Act 2007, Subregulation 1.03 (1). For a full listing see:
http://www.bom.gov.au/water/regulations/schedules/document/Persons_and_Classes_of_Persons.pdf

Figure 2-3 Categories of organizations that must give water information to the Bureau of Meteorology

2.4 Standards and classifications

2.4.1 NATIONAL WATER INFORMATION STANDARDS

The Water Act 2007 and *Water Regulations 2008* contains several definitions of relevance for water quality information derived from remote sensing including any raw data, or any value added information product, that relates to quality of water. This embodies metadata and contextual information relating to water (such as land use information, geological information and ecological information). In addition, this information must comply with applicable National Water Information Standards (NWIS).

The Bureau's Director of Meteorology may, by legislative instrument, issue NWIS relating to water information. In this application the following may be relevant:

- Collecting water information
- Measuring water

- Monitoring water
- Analysing water
- Transmitting water information
- Accessing water information
- Retaining and storing water information

For remote sensing-derived water quality information there are currently no NWIS.

For water quality assessments the specific categories of information are instantaneous measurements of water quality indicators as summarized in Table 2-1. Five of the eight indicators can be directly or indirectly derived from earth observation data.

Table 2-1 Water quality indicators listed in the Water Regulations 2008

INSTANTANEOUS WATER QUALITY INFORMATION	DERIVED FROM EARTH OBSERVATION
Electrical conductivity of a surface water sample collected above the tidal limit of the watercourse (µS/cm at 25 °C)	No
Electrical conductivity of a surface water sample collected above the tidal limit of the watercourse (µS/cm at 25 °C)	No
Total suspended solids concentration of a water sample collected above the tidal limit of a watercourse (mg/L)	Yes-directly derived.
Turbidity of a water sample collected above the tidal limit of a watercourse (NTU)	Yes-directly derived.
Total phosphorus (P) concentration of a water sample collected above the tidal limit of a watercourse (mg/L)	Potentially-via proxy. *In a P-limited system there may be a proxy relationship between CHL and total P.**
Total nitrogen (N) concentration of a water sample collected above the tidal limit of a watercourse (mg/L)	Potentially-via proxy. *In a N-limited system there may be a proxy relationship between CHL and total N.**
pH of a water sample collected above the tidal limit of a watercourse	No
Temperature of a water sample collected above the tidal limit of a watercourse (°C)	Yes-directly derived.

* In Matthews et al. (2011) these possibilities are mentioned. In principle, if nitrogen or phosphorus is the only limiting growth factor, then a proxy relationship with CHL may exist until another limiting growth factor such as light or temperature takes over or until the bio-available nutrient is fully consumed.

2.4.2 AUSTRALIA AND NEW ZEALAND ENVIRONMENT COUNCIL WATER QUALITY GUIDELINES

As part of the NWQMS, ANZECC has developed water quality guidelines (ANZECC 2000, http://www.environment.gov.au/water/publications/quality/pubs/nwqms-guidelines-4-vol1.pdf). The ANZECC guidelines contain detailed scientific information and instructions for Australian water quality including guideline values for toxicants, sediments, physical and chemical stressors and biological indicators (Documents 3-4). Originally published in 1992, the guidelines were last updated in 2000, and now include significant consideration of aquatic ecosystems (Documents 3 &8). These guidelines are currently being reviewed, and updates are anticipated soon.

The ANZECC water quality guidelines provide a framework for water quality management for aquatic ecosystems, recreational water, drinking water and primary industries including irrigation, livestock drinking water, aquaculture and human consumption of aquatic foods.

Notably, the ANZECC water quality guidelines are just that, guidelines, not *standards*. The ANZECC recommends these guidelines should be used to tailor water quality objectives to the large range of environments, ecosystems types and food production systems across Australia and New Zealand. However, the guidelines are intended to be used to prompt action should trigger values be identified.

Table 2-2 provides an example of the ANZECC water quality guidelines. It is a summary of guideline "packages" used to address specific issues that aquatic ecosystems are likely to face from physical and chemical stressors.

Table 2-2 ANZECC water quality guidelines summary of the condition indicators, performance indicators, and location of default trigger value tables in the guidelines for each issue pertaining to aquatic ecosystems

ISSUE	CONDITION INDICATOR/TARGET	PERFORMANCE INDICATORS	PREFERRED METHOD FOR OBTAINING TRIGGER VALUES[a]	DEFAULT TRIGGER VALUE FOR EACH ECOSYSTEM TYPE (TABLES FOUND IN ANZECC, 2000 4(1))	CONSIDER ECOSYSTEM -SPECIFIC MODIFIERS
1. Nuisance aquatic plants	Species composition Cell numbers CHL	TP conc TN conc CHL conc	Reference data Reference data Reference data	Tables 3.3.2, 3.3.4, 3.3.6, 3.3.8, 3.3.10	Yes-Section 3.3.3.1
2. Lack of DO	Reduced DO conc Species composition/abundance	DO conc	Reference data	Tables 3.3.2, 3.3.4, 3.3.6, 3.3.8, 3.3.10	Yes-Section 3.3.3.2
3. Excess of SPM	Species composition/abundance	SPM conc	Reference data	Tables 3.3.3, 3.3.35, 3.3.7, 3.3.9, 3.3.11	Yes-Section 8.2.3.2
4. Unnatural change in salinity	Species composition/abundance	EC (salinity)	Reference data	Tables 3.3.3, 3.3.35, 3.3.7, 3.3.9, 3.3.11	No
5. Unnatural change in temperature	Species composition/abundance	Temperature	Reference data	>80%ile <20%ile	No
6. Unnatural change in pH	Species composition/abundance	pH	Reference data	Tables 3.3.2, 3.3.4, 3.3.6, 3.3.8, 3.3.10	No
7. Poor optical properties	Species composition/abundance	Turbidity Light regime	Reference Data Reference Data	Tables 3.3.3, 3.3.35, 3.3.7, 3.3.9, 3.3.11	No
8. Unnatural flow regime	Species composition/abundance Habitat change % wetted area	Flow regime			

TP=total phosphorous, TN=total nitrogen, CHL=chlorophyll, DO=dissolved oxygen, SPM=suspended particulate matter, EC=electrical conductivity

[a] where local biological and ecological effects data are unavailable

Source: National Water Quality Management Strategy, 2000. ANZECC Guidelines for Fresh and Marine Water Quality Paper No. 4 vol. 1

2.5 Capability: activities with an operational orientation

2.5.1 WATER QUALITY MONITORING

The NWQMS reported that in 1993-1994 there were 1,489 water quality monitoring programs across Australia conducted by governments, universities, research organizations, private companies and community organizations. In 1998-1999 there were 999 programs. It is unknown how many programs are currently being conducted.

As indicated by the water information categories in the *Water Act 2007*, the primary organizations responsible for water quality monitoring are government agencies, principally state government agencies. The NWQA 2011 provides the most synoptic view of the level of current systematic water quality monitoring data coverage in Australia. The assessment evaluated all provided data for standardized sampling, preservation and storage techniques, sampling frequency (NWQA required a minimum of 30 samples for 3 years) and data gaps.

Table 2-3 Primary government agencies responsible for water quality data

STATE/TERRITORY	PRIMARY AGENCY	OTHER AGENCIES/ORGANIZATIONS
Tasmania	Department of Primary Industries, Parks, Water and Environment (DPIPWE)	Local councils, Natural Resource Management groups, Waterwatch, and private organizations
New South Wales	Office of Water	Local councils, catchment management authorities, water authorities
Northern Territory	Department of Natural Resources, Environment, the Arts and Sport (DNREAS)	Local councils and community groups
Victoria	Department of Sustainability and Environment (DSE)	Water authorities, the Department of Health, community groups
Queensland	Department of Environment and Resource Management (DERM)	Local regional and city councils, water authorities and water boards, and community groups
South Australia	Department of Environment and Natural Resources (DENR) and the South Australian Environment Protection Authority	South Australian Natural Resource Management Board and community groups
Australian Capital Territory	Department of Environment, Climate Change, Energy and Water (DECCEW)	Local utility, city council and community groups
Western Australia	Department of Water	Local councils and community groups

Source: Sinclair Knight Merz, 2011. The National Water Quality Assessment 2011. DSEWPaC 2011. Pages 6-7

Currently, all water quality monitoring reported by the NWQA 2011 are discrete point-based samples. The water quality variables summarized in the NWQA 2011 are:

- turbidity
- salinity (measured as electrical conductivity)
- pH
- total nitrogen (TN)
- total phosphorus (TP)
- microbial quality: faecal coliforms, enterococci or *Escherichia coli* (*E. coli*)
- cyanobacterial blooms.

In the NWQA 2011 data coverage is defined by two components, temporal and spatial components. Data were only reported if the data record was complete or nearly complete for three years (> 30 samples). Data were reported by drainage basins (n=12) defined by the Bureau's Geofabric, and by river basins (n=246) defined by the former Australian Water Resources Council.

National water quality monitoring data coverage for the last three years was:

- turbidity was measured in 49% of river basins
- salinity was measured in 50% of river basins
- pH was measured in 44% of river basins
- TN was measured in 45% of river basins
- TP was measured in 44% of river basins

Nationally there is limited data available for cyanobacteria, reported only by the Australian Capital Territory, New South Wales, Queensland, Victoria and Western Australia. Microbial data were even more limited, reported by the Australian Capital Territory, Western Australia and Victoria.

New South Wales has high data availability with 94% of sites having data coverage, as does Victoria, 85%, and Australian Capital Territory with 83% of sites having coverage. Data coverage in the Northern Territory is limited, sampling is primarily event-based or ad-hoc and no water quality variables are measured year-round. The majority of sampling sites in Queensland river basins draining to the north east coast of Australia are monitored quarterly or less frequently, most data coverage is centred in the southeast and central regions of the state. South Australia water quality monitoring is mostly limited to the large coastal rivers and lower Murray system.

Similar patterns of data coverage have been demonstrated by other studies. Bartley and Speirs (2010) reviewed existing sediment and nutrient concentration data in Australia for use in catchment water quality models. Of the available datasets of total suspended solids (TSS), TN and TP, there were 757 entries in the database from 5,114 geographical sites covering 13 different land uses. Approximately 6% had data that could be used to calculate both event concentrations and dry weather or base-flow concentrations at the same site. Forty-one percent of sites had data for all three constituents. For the total database, 70% of sites provided sufficient information to describe the sample collection methods, 85% provided information about the method used to calculate the mean constituent concentration and 26% described the number of samples collected over the hydrograph. Seventeen percent of entries provided sufficient information on the laboratory analytical methods used.

2.5.2 EARTH OBSERVATION DATA PROCESSING CAPABILITY

National-scale remote sensing data infrastructure and the operationalisation of both forward-looking and retrospective analyses of remote sensing data archives are ongoing though Geoscience Australia (GA), and through government-funded research infrastructure networks including the Terrestrial Ecosystem Research Network (TERN), and the Integrated Marine Observing System (IMOS).

GA is Australia's primary satellite ground station and data processing facility, providing scientifically-sound earth observation products, managing long-term satellite earth observation data archives and distribution of satellite data via GA's network of distributors and the Internet. Currently GA provides substantial data from the following satellites and sensors (details about sensors and sensor attributes can be found in Chapter 3):

- Landsat: GA holds extensive archives of Landsat data since the launch of the first sensor in 1979.
- Moderate Resolution Imaging Spectroradiometer (MODIS): GA has been acquiring MODIS data from 2000 to present and provides Nadir BRDF-Adjusted Reflectance (NBAR) products.
- Advanced Very High Resolution Radiometer (AVHRR): Orbiting since 1979, GA collects direct broadcast AVHRR data several times a day.

The TERN includes the AusCover program, the Distributed National Land Cover Remote Sensing Data Facility. Coordinated by CSIRO and supported by the Department of Industry Innovation, Science, Research and Tertiary Education, the program coordinates the production, standardization and inter-operability and open-access to continental scale biophysical map products and earth observation data time-series. Most of the data provided from this program are from MODIS and Landsat. Similarly, CSIRO also leads the satellite data facility of the IMOS, which integrates data from satellite reception stations throughout Australia to derive marine and coastal earth observation products for distribution to the Australian research community.

Currently, for climate and weather monitoring applications many Australian satellite downlink facilities directly transfer their data to CSIRO's High Performance Scientific Computing facility (HPSC). Additionally, a national satellite processing facility is currently being configured at the High Performance Computing and Communications Centre (supported by the Bureau and CSIRO) and the National Computing Infrastructure (NCI; hosted by Australian National University). This national processing facility is a collaborative effort between IMOS, TERN AusCover, GA, the Bureau and the NCI. It will be used to process MODIS, AVHRR and VIIRS data.

Earth observation datasets maybe coupled with *in situ* observations and earth system process models to provide detailed understanding and prediction of environmental processes. This technique is known as data assimilation. Such capability is already established to monitor, assess and forecast the availability, conditions and use of water supply through the Water Information Research and Development Alliance (WIRADA). The WIRADA project is a strategic research investment between CSIRO and the Bureau, resulting in the operationalisation of data assimilation for assessing the distribution of surface waters and forecasting water availability.

The commencement of the eReefs project, a collaboration between CSIRO, the Great Barrier Reef Foundation, the Bureau and other partners, will initiate the development of a state-of-the-art integrated decision support tool for Great Barrier Reef management. A key requirement for eReefs is an operational capability for coastal water quality monitoring, with an ensuing need to also monitor inland water quality following a catchment-to-reef strategy.

In the future, Australian earth observation data infrastructure will be coordinated at a national level. The National Earth Observations from Space Strategic Infrastructure Plan (EOS-SIP), under development by GA and the Bureau as part of Australia's National Space Policy, plans to ensure that current infrastructure will be better coordinated, data networks and computing infrastructure better used, and data reception and transmission reliable at levels necessary to inform future government investment in research and operational infrastructure for earth observation.

2.6 Research capability and activity

Validated earth observation derived ocean water quality products are mature and are being used to advance our understanding of earth and climate science. Whilst the underlying physics of inland water quality are the same as that for ocean colour, remote sensing of inland waters is complicated by the high variability of inherent optical properties (IOPS) (Odermatt et al., 2012). Nonetheless, significant research advances have been made within Australia, though applications are regional in nature, notably along the Queensland-Great Barrier Reef coast and the Murray-Darling system. Current Australian research activity into inland water quality using remote sensing and earth observation is being led by CSIRO, the University of Queensland and the University of Southern Queensland. CSIRO is leading development of *in situ* radiometry for near surface remote sensing of lakes and rivers in Australia, with targeted applications toward continuous water quality monitoring. The state of the science is described in Chapter 3. Several earth observation applications in Australia are illustrated in the case studies described in Chapter 4.

2.7 International developments

"The deterioration of surface water quality through the effects of contaminants, nutrients, excess heat and other factors is arguably the greatest threat to future water availability. Operational observation systems need to be developed and the resulting information systems made compatible and interoperable.

It is feasible to implement a fully operational, spatially comprehensive water quality information system globally relying on systematic observations from past, present and future satellite sensor systems.

Reliable quantitative (temporal and spatial) measures of phytoplankton contents (and blooms) and composition, suspended sediments composition and concentration, dissolved organic matter concentrations, source material identification and light availability assessments for photosynthesis can be provided."

GEO, 2007. Global Inland and Near Coastal Water Quality Information System, GEO Working Group on Earth Observation of Inland and Near-Coastal Waters Work Plan 2010-2015.

Despite international efforts at monitoring global inland water quality, existing data are scarce and declining, have poor geographic and temporal coverage, and may be of questionable accuracy (Strebotnjak et al., 2011). The international coordinating group, the Group on Earth Observations (GEO) recognizes the value of remote sensing to improve understanding of global water quality, forming the Inland and Near-Coastal Water Quality Remote Sensing Working Group with the objective to promote development of improved water quality products (GEO, 2007). GEO's Chlorophyll Globally Integrated Network (ChloroGIN), focusing on MODIS and MERIS products, has recently released demonstration products for some regional lakes based on ocean colour algorithms.

Similar to Australia, there is no national water quality monitoring program in the United States, although under the Clean Water Act, states must monitor water quality and comply with water quality monitoring standards to make data comparable at a national level. The US Geological Survey, the US Environmental Protection Agency and state agencies have funded many inland water quality remote sensing research projects. However, these have all been funded for and conducted at the regional scale. At the national scale the National Aeronautics and Space Administration (NASA) established the NASA Energy and Water Cycle Study with the goal of leveraging their earth observation capabilities to achieve breakthrough improvements to the nation's capability to predict energy and water cycles. As a part of this study, four separate projects are currently investigating inland water quality monitoring, transferability and operationalisation from remote sensing.

In Canada, The National Land and Water Information System (NLWIS) provides an internet-based Geographic Information System (GIS) of up to date information on management of land, soil, water, climate and biodiversity (http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1226588345652&lang=eng). This provides a framework for disseminating Canadian inland water remote sensing products developed by the National Water Research Institute's Aquatic Optics and Remote Sensing Group with support from the Canadian Space Agency. The goal of the group is to provide near-real time daily snapshots of inland water quality on a routine fully automated basis and interpret change in water quality through time series analysis. This is however, still under research and development.

The European Union Water Framework Directive (WFD-2000) implemented in the European Union has a stated goal of good water quality by 2015 through careful monitoring of water quality to achieve good ecological status. This has created the demand for remote sensing water quality monitoring systems. While still in research and development phase, chlorophyll detection from satellite imagery in some regions of Europe has been successfully used to measure ecological status under the WFD (e.g. Brescati et al., 2011).

2.8 Major gaps and opportunities

Current water quality reporting requirements are based on the context of retrospective state, condition and trend analysis. It is clear there is a national need for systematic water quality information, yet many gaps and deficiencies exist. There is an opportunity for earth observation to improve inland water quality monitoring, filling existing gaps by providing synoptic, consistent and comparable data unobtainable through current monitoring technologies and practices.

2.8.1 GAPS

The 2011 biennial assessment of the NWI stated that monitoring is inadequate, particularly around freshwater aquatic ecosystems, reporting that:

- "Accountability for environmental outcomes remains weak. In particular, monitoring capacity is often inadequate and there is a lack of transparent reporting outcomes." (Finding 3.9, NWI 2011 Biennial Assessment).

Further, the assessment highlighted the fact that the NWI was designed to address water quantity rather than water quality, calling this an "obvious gap" that should be addressed and accounted for. The assessment's headline recommendation to address this gap is:

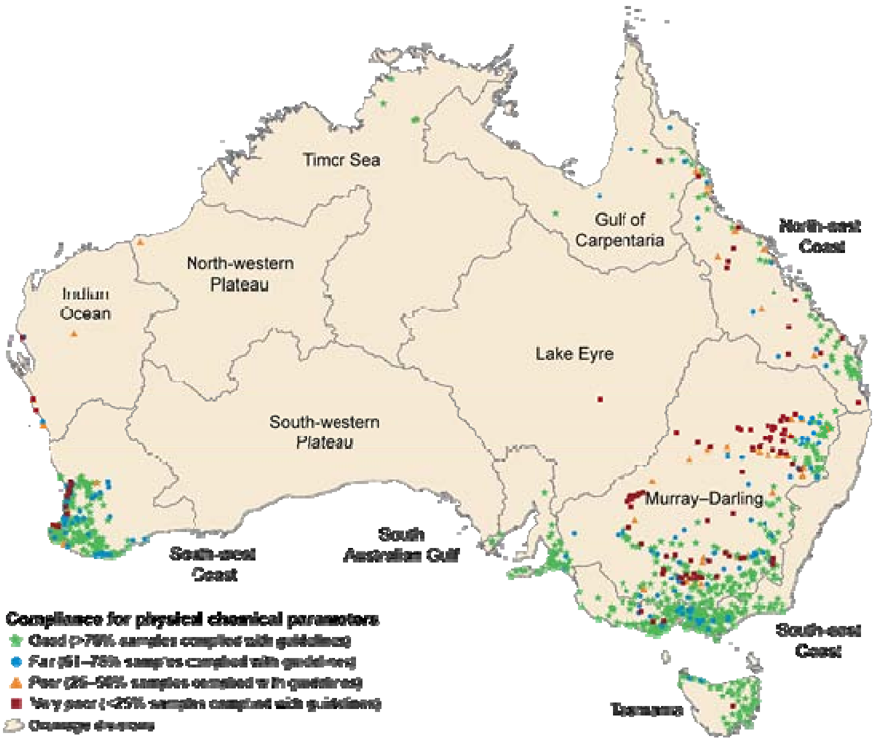
- "Water quality objectives should be more fully integrated into the reform agenda with better connections between water quality and quantity in planning, management and regulation to achieve improved environmental outcomes. There is also a need for a more coordinated and structured approach to urban water quality regulation, at the national level." (National Water Initiative, http://www.nwc.gov.au/reform/assessing/biennial/the-national-water-initiative-securing-australias-water-future-2011-assessment).

The number of water quality monitoring programs in 1993-1994 and 1998-1999 decreased from 1,489 to 999, a decline of 33% in the number of locations where inland water quality measurements are available. Although similar data were not available for the period through 2011, the NWQA highlights the poor data coverage (spatially and temporally), lack of consistent sampling and lack of data accountability (NWQA, 2011). This severely impacts the effectiveness of the Bureau's task of AWRA reporting on water quality. The NWQA 2011 identified several gaps in inland water quality monitoring information:

- Considerable variation in data availability, with notably less data available for cyanobacteria blooms
- Issues with data acquisition and accessibility
- A need to examine the implications of extreme events on water quality

Bartley and Speirs (2010) concluded that there are still large areas of Australia for which no data exist. The NWQA 2011 concurs. Coverage of water quality monitoring information across the country is poor. There is extremely limited monitoring in the Northern Territory, Queensland, South Australia and the Eastern part of Western Australia. The reasons cited for this are remoteness; they are difficult logistically and expensive to access. Further, the seasonality or ephemeral nature of many of the water bodies in this region result in infrequent or inconsistent data collection. For example, only 10% of sites with water quality data in Western Australia had sufficient data for the NWQA 2011. The only locations where cyanobacteria are routinely monitored are New South Wales, ACT, and limited parts of Victoria and Queensland (NWQA 2011).

Figure 2-4, reproduced from the NWQA 2011, shows the distribution of sites used in turbidity compliance reporting for the SoE 2011 report. The map depicts the distribution of sites that met with NWQA data requirements, including standardized sampling, preservation and storage techniques, data gaps and sampling frequency (>30 samples over 3 years).



Source: Reproduced from Sinclair Knight Merz, 2011. The National Water Quality Assessment 2011. SEWPaC 2011. Pages 6-7.

Figure 2-4 Compliance with the ANZECC 2000 guidelines for turbidity from 2000-2010

Poor coordination between states and lack of consistency in the methods and actual water quality variables measured has made assessing long term trends difficult. A systematic approach that measures the same water quality variables at regular intervals across a wide geographic range is required for effective water quality SoE reporting.

2.8.2 OPPORTUNITIES

Earth observation provides the opportunity to measure a consistent suite of water quality variables across a large region simultaneously (synoptic sampling), including accessing remote areas at regular sampling frequency, thus addressing many of the current gaps in national water quality monitoring.

There is no current operational system for monitoring inland water quality using earth observation in Australia. However, there is a national move to operationalise earth observation for coastal and continental shelf water quality. Ongoing international developments towards operationalising inland and coastal water earth observation will benefit Australia.

The advent of new operational remote sensing sensors and supporting infrastructure such as TERN and IMOS provide new opportunities for developing an operational inland water quality monitoring capability for Australia. Existing computing and data processing infrastructure will lessen the investment needed to operationalise an inland water quality monitoring capability.

An important characteristic of earth observation data is that a significant amount of environmental information is “hidden” within satellite image archives. Each image collected over Australia that is archived contains potential water quality information of relevance to establish environmental baselines, trends and anomalies as well as insights into extreme events such as flood or algal blooms.

The current methods for obtaining water quality information from satellite imagery can be retrospectively applied with a significant level of confidence. Many water management and water research agencies are unaware that this archival information exists and may be able to augment and extend time series of water quality information back as far as 1984. Earth observation derived water quality information across national and state scales would be conducive to more systematic and long term-relevant SoE reporting than the current state of monitoring.

The following chapters will detail these concepts.

3 Inland Water Quality Detection and Monitoring

The gaps and opportunities discussed in Chapter 2 provide evidence that the state of water quality monitoring in Australia is insufficient for a national scale assessment of inland water quality. This chapter provides an overview of inland water quality monitoring sampling considerations and methods that should be accounted for when designing a national-scale operational inland water quality monitoring program.

3.1 Temporal sampling considerations

There are two primary temporal considerations for inland water quality monitoring. The first is sampling designed to represent the dynamics of water quality and the range of conditions that can occur over diurnal, seasonal and annual cycles. The second temporal consideration is sampling designed to develop a time series. Time series are essential for assessing the condition and trends of inland water quality as they relate to the effect of water quality management and climate change.

Many Australian inland waters are exposed to cycles of long periods of relative low flow or drought conditions, interspersed with intense periods of rainfall leading to flash floods in high relief terrain or extended and extensive floods in flat terrain. Floods cause large fluxes of suspended sediment, dissolved organic material, salt, nutrients and contaminants which can lead to changes in environmental state in aquatic ecosystems. In the wet tropics higher flows occur throughout the year.

Under stable or drought conditions seasonal algal species composition and growth, and salinity are considered important variables to monitor. More frequent sampling is required when algal blooms are likely to affect water quality.

During intense rainfall and resulting stream-flow events the focus changes to estimating fluxes of material such as suspended sediment and organic matter. Algal-related measurements are less relevant as water turbulence and the re-suspension and dissolution of soil materials prevents algal growth. Monitoring rapid changes in water quality during extreme events poses challenges to any monitoring method. Nevertheless this challenge must be met if increased understanding of the effects of extreme flow events on the aquatic ecosystems is to be better understood.

For improved understanding of effects of climate variability and possible climate change on inland water quality a re-analysis of historical *in situ* data may be necessary. Retrospective processing of satellite images, archives of which date back to 1984, may also reveal temporal changes, trends and anomalies across Australian inland water systems.

Hydrodynamic and biogeochemical models of inland water bodies, provided they are well parameterised by valid data may provide additional insight into historic, current and future water quality conditions and trends.

3.2 Spatial sampling considerations

In Australia there is a significant difference in the amount of water quality sampling performed between the more densely populated parts of the country and the more remote, sparsely populated parts of the country.

There are approximately 149,000 water bodies in Australia.

- 2% are larger than 1km^2 = ~2,300 water bodies = ~11% of surface area = ~77,500 km^2
- 42% are larger than 0.01 km^2 = ~63,000 water bodies = ~ 32% of surface area = ~220,000 km^2

Water quality sampling must be spatially representative of these water bodies to provide understanding of system processes, such as heterogeneity, environmental flows, interrelationships between water bodies and catchment run-off effects. Water quality managers require spatially intensive measurement or modelling to optimise the location of their *in situ* point sampling or permanent instrumentation for water management purposes. Spatially intensive sampling is also useful for parameterising hydrodynamic and biogeochemical models.

End-user requirements should determine the optimal spatial sampling scheme. However, logistical, operational and financial constraints usually prevent an optimal sampling scheme from being realized. Due to the reality of limited resources, limited spatial representation is proscribed by *in situ* approaches. Extensive distances in Australia make capturing the spatial distribution of measurements using *in situ* methods infeasible (e.g. Lake Eyre Basin waters). Unless an intense *in situ* measurement campaign is performed, little or no information is available on spatial variability, potentially impeding design decisions. *In situ* sampling strategies are often difficult to implement under extreme flow conditions or across flooded land.

There are two different ways to design spatial sampling strategies: design based sampling and model-based sampling (Gruijter, 1999). Classical survey sampling typically employs design-based sampling. In this approach, the population is fixed and the sampling locations are random. In model-based sampling the population is considered random and the sampling locations are fixed. Geostatistical methods are more likely to use a model-based design.

Most traditional *in situ* water sampling follows characteristics of design based approach (Gruijter, 1999).

- The required result is an estimate of the distribution of the variable such as the mean and the standard deviation.
- At least 5 to 10 sampling points can be afforded, depending on the spatial variation.
- It is practically feasible to locate these points randomly.
- It is important to obtain an unbiased estimate.
- It is important to obtain an objective assessment of the uncertainty of the estimate.

The design-based approach is close to the current practice of water quality sampling in Australia. However the criteria of randomness and correct probability in sampling design are often disregarded in favour of convenience sampling and purpose-based sampling (e.g. algal bloom initiation).

When more spatial comprehensive data are available, the model based approach is better suited for sampling design. This approach has the following characteristics (Gruijter, 1999):

- The required result is prediction of values at individual points or the entire spatial distribution in the area.
- A large number of spatial points are available.
- There is a reliable model of the spatial variation.
- High spatial correlation exists in the area.

Earth observation-derived water quality information can be used to shift water quality monitoring sampling design in Australia from design-based to model-based sampling approaches, thus allowing predictions of water quality for entire water bodies or catchments.

3.3 Spatially and temporally representative sampling stations

For national-scale spatially and temporally representative water quality monitoring, Australia needs a range of sampling stations of different sampling densities and frequency and of different water quality variables (Nixon, 1996):

- Statutory stations to provide data to fulfil legal state or commonwealth commitments.
- Benchmark (or reference) stations to characterize catchments undisturbed, as far as possible, by humans.
- Boundary stations to characterize fluxes, either between legal boundaries, or between media (e.g. from a river to a lake or ocean, or from a surface stream to groundwater).

- Impact stations that aim to control the effect of well-defined pollution sources.
- Representative stations that can be used to provide summary information on a larger area, usually with long records.
- Operational stations that are located for day-to-day water quality management by local, regional or national agencies.
- Research stations that are installed and operated during scientific projects.

There are also examples of aggregating or summarising data from several sampling stations to characterize relatively large areas or catchments. These aggregations have been termed “virtual stations” (Santos and Costas, 1991). There are three types of virtual water quality monitoring stations relevant to Australia:

1. *Reference stations* provide reference points for the natural or pristine water quality conditions likely to have existed across Australia. These reference points can be use to understand how water quality is changing with time.
2. *Flux stations* provide estimates between media, between states, and to coastal waters.
3. *Representative stations* provide an assessment of general water quality across Australia.

For national-scale inland water quality monitoring and reporting, using virtual stations of all three categories may provide a balanced national assessment of inland water quality.

3.4 Data sources

Three types of water quality measurement methods suitable for water quality monitoring can be identified:

1. *In situ* discrete water sampling for field and laboratory analysis.
2. *In situ* continuously deployed, automated physicochemical and bio-optical instruments and samplers.
3. Remote sensing based methods from just above water through to satellite observations.

In the following sections these three methods will be discussed systematically.

3.4.1 *IN SITU* DISCRETE SAMPLING

Historically, point-based *in situ* discrete sampling has been the only way in which water quality management authorities could assess the condition of inland waters. The frequency at which point-based sampling programs are carried out may vary from daily for drinking water reservoirs to weekly, monthly or seasonal. Sampling schedules may often be dependent on perceived threats and/or the intended uses for the water. Currently, most water quality monitoring programs rely on discrete *in situ* point samples.

Advantages

1. A wide range of field and laboratory analyses can be performed for determinations of algae, cyanobacteria, zooplankton and other micro-fauna and flora.
2. A wide range of physicochemical analytical measurements can be performed for concentrations and forms of suspended matter, dissolved organic carbon, nutrients, and organic and inorganic micro-pollutants.
3. The measurements are usually highly replicable within a sample (high precision). Depth profiles of samples can also be taken to reveal lake structure (e.g. above and below the thermocline to show stratification effects).
4. Sampling is, with the exception of extreme weather and flood events, weather independent.
5. The longest-term records of water quality come from *in situ* discrete measurements.

Limitations

1. Logistical difficulties. Point-based sampling requires staff to travel with sampling gear to platforms such as jetties and bridges or access the water body using a boat to retrieve samples for analysis. Sampling *in situ* during extreme events may be dangerous and logistically difficult to implement.
2. Sufficient spatial representation is difficult to achieve. Extensive distances in Australia make capturing the spatial distribution of concentrations infeasible (e.g. Northern Territory, Lake Eyre Basin waters).
3. Timing of point sampling does not necessarily coincide with actual water quality events of interest. The relatively low frequency of sampling over most waters means that most often baseline conditions are sampled. Intense but high impact events may be entirely missed.
4. Breaks in the sampling effort. The extensive nature of many of Australia's water ways and the remoteness of lakes and reservoirs also makes the maintenance of point sampling programs a challenge; as priorities, costs and funding change, the records show many water sampling programs run for a few years and are then relocated or discontinued.
5. Sample variation. Although standards are improving, there is no legislative requirement to use specific well calibrated, well documented and Australia-wide standard analytical methods. This makes inter-comparison of results measured in different laboratories difficult.
6. Unavailability of data. A disadvantage for national inland water quality environmental reporting is that the results of many *in situ* sampling programs are not made fully publicly available.

3.5 *In situ* autonomous high frequency sampling

There have been significant technological developments in such instruments such as increased sensitivity, increased number of variables that may be measured as well as sensor-to-base connectivity. *In situ* systems can be active 24 hours per day and can thus capture daily and diurnal as well as extreme events. In many circumstances, *in situ* autonomous high frequency measurement systems provide the only means for high frequency measurements.

Examples of *in situ* measurements from permanently installed instrumentation vary from the bio-optical to the physicochemical. Bio-optical measurements include fluorescence measurements of algal pigments, fluorescence of CDOM, nitrates derived from absorption of UV wavelengths and turbidity usually derived from laser backscattering. *In situ* physicochemical measurements include electrical conductivity, salinity, dissolved oxygen and temperature.

Advantages

1. The ability to measure several physicochemical and bio-optical variables at one location with high sensitivity.
2. The capability to perform discrete data collection on-demand or continuously.
3. *In situ* sensors can store data onboard, or transmit data in (near) real time using radio telemetry, mobile phone or wireless networks.

Limitations

1. *In situ* autonomous systems cannot currently measure the same amount of variables that can be determined from *in situ* sampling and laboratory analysis.
2. Some variables such as algal pigments are measured using fluorescence signals, a relationship that may vary with algal photosynthetic state and thus not truly reflect algal biomass.
3. Logistical challenges from installation, power requirements, and maintenance (from bio-fouling and other fouling). Vandalism or extreme flow events can destroy instrumentation leading to capital loss.

4. Poorly resolved spatial representation. *In situ* instruments make point-based measurements that may not represent the spatial variability of a lake or river.
5. During flood events conditions in extensive floodplains will not be sampled using such fixed measurement approaches.

3.5.1 REMOTE SENSING OBSERVATIONS

Earth observation has the potential to provide spatially and temporally comprehensive information on a limited set of water quality variables, derived from reflectance information in the visible, nearby infrared and thermal infrared wavelengths (outlined in chapter 1.3.1.).

Remote sensing approaches can also employ above water *in situ* spectroradiometers or digital cameras which can function under cloud cover and other atmospheric conditions adverse to earth observation.

The frequency of remote sensing measurements varies, but in general it is higher than *in situ* sampling programs, especially for more remote areas. However, temporal frequency is much lower than *in situ* continuous measurement systems (with the exception of *in situ* spectroradiometers or digital cameras that can have similar measurement frequencies during daytime conditions).

What is directly measureable from space?

- Directly measureable optical water quality variables: CHL pigments, cyanobacterial pigments, TSM, CDOM, K_d and the derived variables of Secchi disk transparency and turbidity.
- Surface algal blooms as well as emergent and submerged aquatic vegetation.
- Temperature of the water surface skin layer using thermal infra red (TIR) earth observation.

What is indirectly measureable from space?

- By making use of the combined information in directly measurable optical properties it is possible to derive information about eutrophication, environmental flows, carbon and primary productivity.
- Non-optical products estimated through inference, proxy relationships or data- assimilation with remotely sensed optical properties are nitrogen, phosphate, organic and inorganic micro-pollutants and dissolved oxygen. However, these relationships are stochastic, may not be causal and may have a limited validity range.

Advantages

1. Large varieties of measurement scales and repeat visit times. Pixels sizes vary from 2m to 1 km, and image swaths vary from as narrow as 16 km to 2,200 km. Time scales vary from days to near monthly, as well as on demand.
2. Spatially synoptic measurements and objectivity across all Australian states and territories.
3. Increasing numbers and sophistication of satellite and airborne sensors result in increasing data availability and greater chance of continuing data acquisition longer term.
4. Data archives available back to 1984 may be retrospectively processed for water quality.
5. Generally decreasing costs for data acquisition over time, especially in the high spatial resolution satellite sector as competition has increased.
6. Increasingly robust algorithms for water quality measurements published in international peer review literature (see Matthews, 2011; Odermatt et al., 2012) for recent reviews).
7. Increasingly used internationally for operational environmental monitoring and research programs, including oceanic and coastal water quality monitoring.
8. Once the algorithms have been parameterised, the determination of water quality variables may be achieved independent of *in situ* data.

9. If the bottom has a measureable signal at the surface of the water body bathymetry can be assessed as well some information on bottom type and bottom cover. Methods exist to detect submersed and emergent macrophytes.

Limitations

1. Weather dependency. Effective revisit frequencies may be compromised by adverse atmospheric conditions, which are dependent on season and geography (Table 3-2).
2. Potential temporal bias. Cloud, haze, fog, smoke or dust may be seasonally biased leading to a bias in frequency of earth observations over a target area (e.g. full or partial cloud cover in the monsoon in the north, low pressure systems in the south, smoke in dry summer conditions).
3. Limited suite of water quality variables is detectable. Remote sensing is restricted to variables that have a direct influence on water optical conditions. Indirect measurement methods are required to infer non-optical products through inference, proxy relationships or data- assimilation.
4. Surface only view. As most of the remote sensing signal is derived from the top one or two meters of inland waters, earth observation provides surface water quality measurements only.
5. Shading by plant canopies along shorelines may obscure useful reflectance signals from riverine and small pond systems.

3.6 Resolution considerations for earth observation

Spatial resolution determines the limits of the finest spatial detail measureable (the pixel size) and temporal resolution represents the nominal frequency with which images of the same area are acquired (irrespective of atmospheric conditions). Spectral resolution determines for each pixel how detailed the spectral reflectance can be measured and radiometric resolution refers to the absolute amounts of reflectance that can be measured by the sensor. In essence, the spatial and temporal resolutions determine the monitoring capability in time and space and the spectral and radiometric resolutions determine how many water quality variables can be discriminated with what level of accuracy. Table 3-1 provides an overview of existing and upcoming satellite sensor systems of relevance for inland water quality in Australia and the sensors' suitability toward measuring optical water quality variables.

Table 3-1 Existing and near-future satellite sensor systems of relevance for inland water quality in Australia

SATELLITE SENSOR SYSTEMS		PIXEL SIZE (M)	SPECTRAL BANDS (400-1000NM)	REVISIT CYCLE	RAW DATA COST PER km^2 (AUD)[a]	WATER QUALITY VARIABLES[b,c]					
						CHL	CYP	TSM	CDOM	K_d	TURB SD
***Current* ocean-coastal low spatial resolution**	MODIS	1000	9	Daily	Free	Highly Suited	Potential	Highly Suited	Highly Suited	Highly Suited	Highly Suited
	MODIS	500	2	Daily	Free	Not Suitable	Not Suitable	Potential	Potential	Potential	Potential
	MODIS	250	2	Daily	Free	Not Suitable	Not Suitable	Potential	Not Suitable	Potential	Potential
	MERIS & OCM-2	300	15	2-3 days	Free	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited
	VIIRS & JPSS	750	7	2x/day	Free	Suitable	Potential	Potential	Suitable	Suitable	Suitable
***Current* multi-spectral mid-spatial resolution**	Landsat	30	4	16	Free	Potential	Potential	Suitable	Suitable	Suitable	Suitable
***Current* high spatial resolution[a]**	IKONOS, Quickbird, SPOT-5, GeoEYE	2-4	3-4	On-demand 2-60 days	5-15	Potential	Potential	Suitable	Suitable	Suitable	Suitable
	RapidEye	6.5	5	Daily	1.5	Potential	Potential	Suitable	Suitable	Suitable	Suitable
	Worldview-2	2	8	On-demand	30	Suitable	Suitable	Highly Suited	Suitable	Highly Suited	Highly Suited
***Future* ocean-coastal low spatial resolution**	Sentinel-3	300	21	Daily	Free	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited
***Future* multi-spectral mid-spatial resolution**	LDCM	30	5	16	Free	Suitable	Potential	Suitable	Suitable	Suitable	Suitable
***Future* hyper-spectral**	EnMap	30	90	On-demand	Free (?)	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited
	PRISMA	20	60	25 days	Free (?)	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited
	HySpIRI	60	60	19 days	Free	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited	Highly Suited

● Highly Suited ● Suitable ● Potential ● Not Suitable

CHL=Chlorophyll; CYP=cyanobacterial pigments such as cyano-phycocyanin and cyano-phycoerythrin; TSM=total suspended matter; CDOM =coloured dissolved organic matter; K_d= vertical attenuation of light coefficient; TURB= turbidity; SD=Secchi Disk transparency

[a] Raw data costs are per image. Bulk acquisitions may attract a discount.

[b] Products in development are: coarse particle size distributions and phytoplankton functional types.

[c] Model-management integrated products under research are: eutrophication index, water quality index, algal bloom index, carbon content/flux and contaminant estimation.

3.6.1 SPATIAL AND TEMPORAL RESOLUTION

Satellites operate outside of the earth's atmosphere. There are two types of orbits for satellite sensors: geostationary and polar orbiting.

Geostationary satellites are located above the equator at a distance of approximately 36,000 km. Due to this distance geostationary satellites typically have a spatial resolution of 5 km, although a recently launched geostationary ocean colour satellite GOCI, measures at 1 km resolution. Geostationary satellites can image at high temporal frequency (e.g. once every 15 minutes) potentially providing near continuous monitoring over dynamic features such as coastal ecosystems, river plumes and tidal fronts. Combined with advances in imaging spectrometer technologies 'high' pixel resolution (e.g. 250 m) is possible, however the physical limit to spatial resolution will be in the order of 100 m pixels. A future development for Australia may be geostationary satellites above the continent with 1 or 0.5 km pixels but with high spectral resolution. This however, remains a potential for the future.

Currently Australia relies on polar orbiting satellites for water quality assessment. Polar orbiting satellites pass near the earth's poles in a sun-synchronous orbit at an altitude of 450 to 800 km. A typical earth orbit lasts about 100 minutes. Polar orbiting satellites have a trade-off between spatial resolution and temporal resolution: high spatial resolution means that the temporal resolution is lower and vice versa. Depending on the imaging swath of a particular satellite sensor, a picture of the earth is built up over consecutive passes varying in time from a single day (e.g. MODIS type sensors with a swath width of 2,200 km); once every 2 to 3 days (MERIS and OCM-2 type sensors with swath widths of about 1,200 km); once every 16 days (Landsat 5 and 7 with swath widths of 180 km); or once every 60 days or more (SPOT 5, Worldview-2, IKONOS, QuickBird, RapidEye with narrow swath widths typically around 15 to 77 km wide). The RapidEye system is a constellation or 'swarm' of 5 satellites that are pointable in space resulting in a possible daily coverage of targeted areas on the earth's surface.

As Australia covers temperate to tropical climatic zones across continental to coastal regions the effective temporal resolution will be 20 to 80% less than the nominal temporal revisit frequency due to the range of cloud cover across the continent. Table 3-2 summarises the mean percent of cloud cover for North and South Australia. The mean percent cloud cover was determined from 26 years (1983-2009) of global cloud data.

Table 3-2 Mean percent cloud cover for northern and southern Australia

SEASON	NORTH	SOUTH
Sep-Oct-Nov	10%	80%
Dec-Jan-Feb	70%	25%
Mar-Apr-May	25%	75%
Jun-Jul-Aug	15%	75%

Source: http://isccp.giss.nasa.gov/products/browsed2.html

An additional interference in images over water targets is the possible occurrence of sun and sky glint arising from surface reflectance of light from individual wave facets. The chance of sun glint interference is increased with pointing satellite sensors if the sensor pointing angle interacts adversely with the water surface and the angle of reflected sun and sky light. For sensors with large swaths (such as MERIS and MODIS) extreme grazing angles at the edges of the swath causes degradation of the measured signal for similar reasons. Although algorithms are available to remove sun and sky glint, it is still a phenomenon to be avoided if possible.

When considering spatial resolution requirements for inland water quality measurements, it is important to consider the pixel size of the sensor system relative to the size of the water bodies of interest. In order for a sensor to effectively measure a water body, the body of water must be at least three to four times the size of a pixel to ensure the pixel is of "pure" water and does not contain any significant signal component from surrounding land and vegetation. Thus, to resolve a lake at 30 m pixel resolution, a minimum of 9 (3 x 3) "pure" water pixels, but preferably 16 (4 x 4) pixels or a 120 by 120 m lake area is required.

Table 3-3 summarises the number of water bodies that may be reliably assessed at MODIS (250m)/MERIS (300m) and Landsat (30 m) resolution (at 1,000,000 m^2 and 14,400 m^2, respectively). The table provides the total number of water bodies discriminable at the two different sensor resolutions for each state and for the nation as a whole (Number). It also provides the total area of each water body type for each state, and the percentage of those areas that are discriminable at the two sensor resolutions. Note that the number of water bodies discriminable may be below 1% yet still have considerable areas as a few large lakes will be resolved. See 8 for more detail. The accompanying Figure 3-1 proves an example of the GIS layers used to provide this summary.

Table 3-3 Amount of water bodies that may be resolved by MODIS-MERIS and Landsat resolution

	WATER BODY TYPE	NUMBER	MODIS-MERIS 1000 m	LANDSAT 120 m	TOTAL AREA (km^2)	MODIS-MERIS 1000 m	LANDSAT 120 m
West Australia	Lake	55,088	1%	12%	38,850	30%	98%
	Watercourse Area	4,571	<1%	58%	4,595	1%	92%
	Land Subject to Inundation	3,052	6%	95%	23,775	18%	>99%
	Swamp	1,272	1%	71%	612	2%	>99%
	Town Rural Storage	92	3%	88%	1,149	57%	>99%
	Settling Pond	63	5%	95%	155	15%	>99%
Northern Territory	Lake	9,693	1%	30%	93,096	2%	5%
	Watercourse Area	1,435	<1%	38%	27,696	<1%	3%
	Land Subject to Inundation	4,482	4%	93%	241,511	2%	6%
	Swamp	1,336	4%	94%	32,579	3%	8%
	Town Rural Storage	27	4%	85%	10,721	<1%	0%
	Settling Pond	18	0%	89%	150	0%	7%
Queensland	Lake	16,614	<1%	30%	5,527	30%	67%
	Watercourse Area	3,325	<1%	40%	4,402	1%	26%
	Land Subject to Inundation	4,916	6%	98%	74,438	17%	42%
	Swamp	3,625	2%	94%	4,288	13%	68%
	Town Rural Storage	1,070	1%	83%	1,509	13%	70%
	Settling Pond	68	1%	78%	57	4%	72%
South Australia	Lake	18,325	1%	52%	39,740	50%	76%
	Watercourse Area	616	1%	60%	1,897	4%	47%
	Land Subject to Inundation	1,485	9%	90%	21,505	6%	26%
	Swamp	751	2%	83%	540	10%	67%
	Town Rural Storage	38	0%	89%	26	0%	42%
	Settling Pond	29	0%	69%	17	0%	59%
Victoria	Lake	2,941	2%	56%	2,402	31%	78%
	Watercourse Area	145	0%	27%	420	0%	1%
	Land Subject to Inundation	946	6%	93%	4,957	14%	56%
	Swamp	526	2%	96%	654	4%	70%
	Town Rural Storage	224	5%	68%	900	15%	68%
	Settling Pond	40	3%	93%	36	3%	69%
New South Wales	Lake	5,608	3%	74%	8,105	34%	96%
	Watercourse Area	759	0%	54%	1,015	0%	87%
	Land Subject to Inundation	2,478	8%	96%	40,600	27%	75%
	Swamp	1,264	3%	96%	3,595	13%	98%
	Town Rural Storage	801	3%	91%	1,421	10%	91%

	Settling Pond	39	0%	85%	22	0%	100%
Tasmania	Lake	558	1%	85%	364	10%	40%
	Watercourse Area	112	0%	10%	239	0%	<1%
	Land Subject to Inundation	99	3%	88%	101	6%	66%
	Swamp	568	2%	91%	541	3%	68%
	Town Rural Storage	86	16%	99%	1,197	38%	86%
	Settling Pond	4	0%	100%	3	0%	33%
Australian Capital Territory	Lake	3	0%	33%	<1	0%	<1%
	Watercourse Area	2	0%	50%	<1	0%	0%
	Land Subject to Inundation	0	0%	0%	0	0%	0%
	Swamp	0	0%	0%	0	0%	0%
	Town Rural Storage	9	0%	89%	13	0%	15%
	Settling Pond	3	0%	67%	<1	0%	<1%
Australia	Lake	108,830	1%	28%	188,085	21%	46%
	Watercourse Area	10,965	<1%	49%	40,265	<1%	20%
	Land Subject to Inundation	17,458	7%	95%	406,887	8%	27%
	Swamp	9,342	2%	90%	42,809	5%	25%
	Town Rural Storage	2,347	3%	86%	16,936	9%	31%
	Settling Pond	264	2%	85%	441	6%	60%

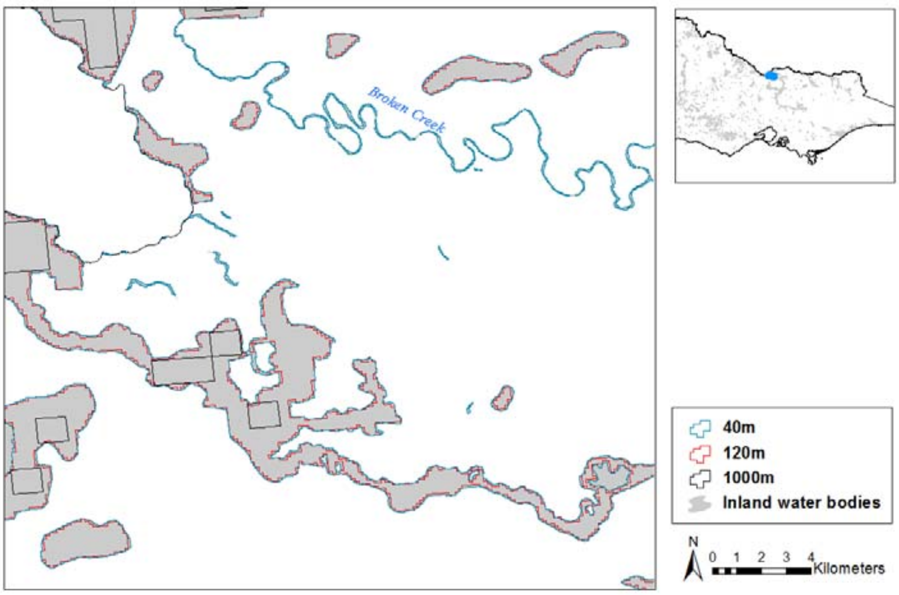


Figure 3-1 Example of GIS data layer analysis required to create table 2 for Broken Creek area in Victoria

There are approximately 149 thousand water bodies (lake, land subject to inundation, settling pond, swamp, town rural storage and water courses) in Australia.

- 2% can be imaged by MODIS (250 m) and MERIS (300m) pixels = ~ 2,300 water bodies
- 42% can be imaged by Landsat (30m) pixels = ~ 63,000 water bodies

In terms of area possible to be assessed by earth observation from these two sensor types:

- 11% of the total area can be imaged by MODIS (250 m) and MERIS (300m) pixels = ~ 77,500 km^2
- 32% of the total area can be imaged by Landsat (30m) pixels = ~220,000 km^2

This spatial resolution issue has consequences for imaging small water bodies such as small or medium width river systems. In such situations high spatial resolution imagery (with pixel sizes of 2 to 10 m) may be the only option, possibly leading to significant data acquisition costs. A multi-resolution approach is most cost-effective, where coarse (but frequent) satellite imagery is used for all larger lakes, reservoirs and river sections and, only when necessary is high resolution imagery acquired and processed. Figure 3-2 shows the examples of the influence of spatial resolution from 2 meter to 300 meter pixels on the ability to resolve Lake Burley Griffin in the ACT.

Rather than imaging all water bodies, the virtual station concept would systematically image a selection of water bodies that are representative of the associated aquatic ecosystem (be it natural or artificial). This would be especially effective for smaller or narrow water bodies reducing the need for high resolution imagery and thus reducing cost. For larger water bodies this is a less useful strategy as processing high spatial resolution 10 by 10 km scenes is as much work as processing a low spatial resolution 1,000 by 1,000 km scene.

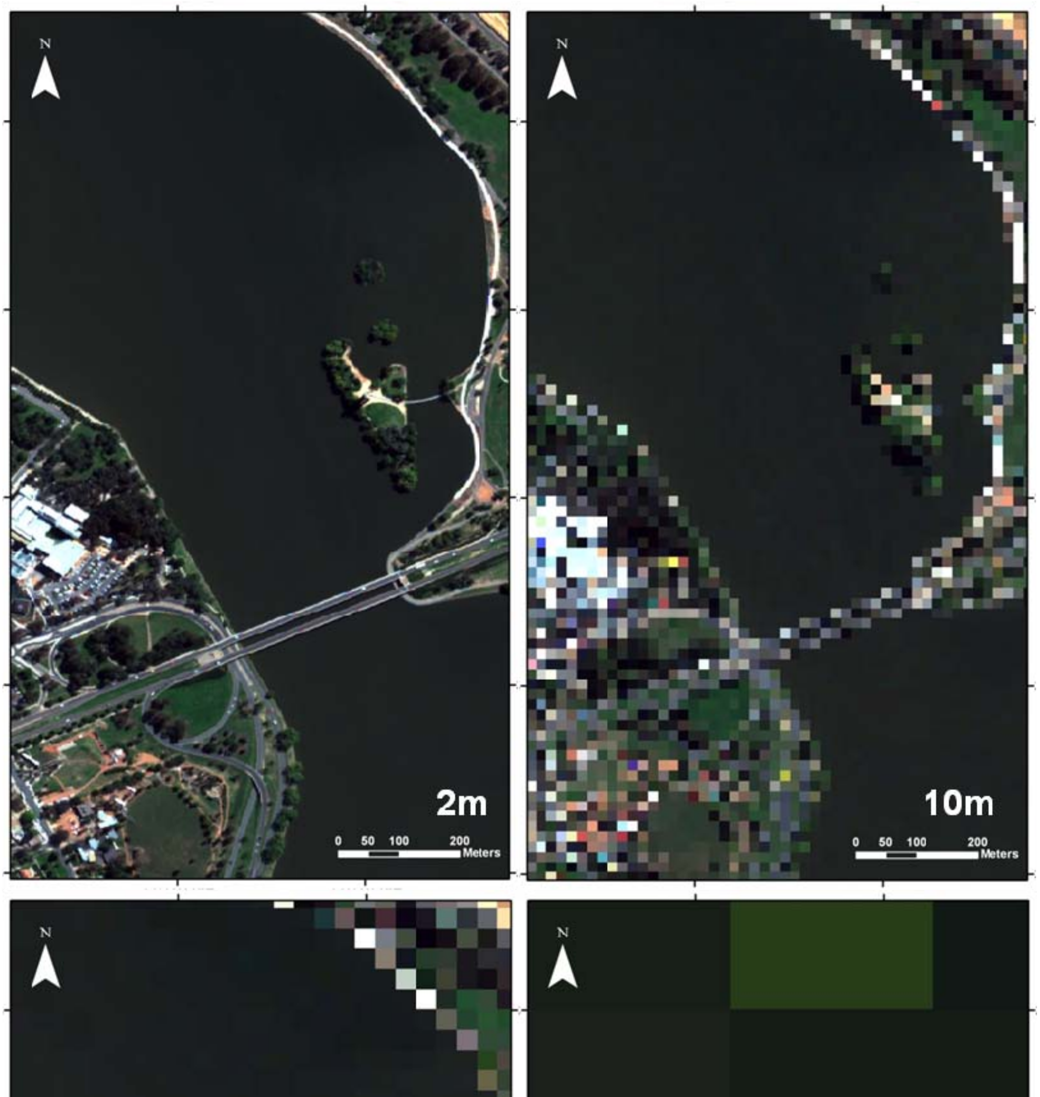


Figure 3-2 The influence of spatial resolution for a Lake Burley Griffin satellite image showing the Commonwealth Bridge

3.7 Spectral and radiometric resolution

For satellite based earth observation the number, width and placing of spectral bands in the visible and nearby infrared wavelengths (the wavelengths that can penetrate the water column) determine the amount and accuracy of water quality variables that are discernable from a water body. Table 3-1 presents an overview of satellite sensor spectral specifications and their potential applications for inland water quality assessment.

Sensors with three to four broad spectral bands (multispectral sensors) can be used to detect TSM, K_d, Secchi disk transparency, turbidity and CDOM, if a blue spectral band is available. Algal pigments such as CHL may be detected. However, at low concentrations accuracy will be low as broad spectral bands cannot discriminate the more narrow pigment spectral absorption features from other absorbing and backscattering materials in the water column.

As sensors have more, narrower and suitably positioned spectral bands (e.g. MODIS, MERIS and OCM-2) CHL becomes an accurately measureable variable. As the bands are better positioned and well distributed across the visible and nearby infrared spectrum (WorldView-2 with 8 spectral bands or MERIS with 15 spectral bands) phytoplankton pigment types become detectable such as the cyanobacterial pigments (CPC and CPE).

Although still in research phase, finer spectral resolution may also make it possible to estimate particle size distribution as well as fractions of organic and mineral particulate matter. The highest form of spectral resolution for earth observing sensors is the hyperspectral band configuration where the entire visible and nearby infrared spectrum are measured in narrow (5 to 20 nm wide) contiguous bands. Because the high spectral resolution of these sensors provides a complete reflectance spectrum, they are often termed “imaging spectrometers.”

Radiometric resolution determines the lowest level of radiance or reflectance that the sensor can reliably detect per spectral band. In essence this is related to the amount of photons recorded and the quality of conversion of a light signal measured by a detector (in volts) to a digital number. Using the same detector and A:D converter technology, fine spatial resolution sensors will have lower radiometric resolution than coarse spatial resolution sensors, as the area imaged reflects fewer photons. Similarly, narrow spectral bands record fewer photons. Thus, as the spectral and spatial resolution increases the useful signal relative to noise in the data decreases. However, this trade-off in spectral, spatial and radiometric resolution is countered by increases in detector sensitivity on satellite sensors; in general, more modern sensors have an overall higher radiometric sensitivity than older sensors.

3.8 Status of retrieval of water quality variables from earth observation

3.8.1 OPTICAL REMOTE SENSING OF WATER QUALITY

Optical remote sensing of water quality makes use of the fact that water column constituents transform the light entering the water by transmitting, absorbing or scattering the incoming sun and sky light. A schematic presentation of these processes is presented in Figure 3-3.

Solar irradiation (light) at the top of the atmosphere interacts with the atmosphere in the form of light absorption and light scattering. Once near the water surface this light is composed of direct sun light and diffuse skylight (which has a blue colour under clear sky conditions and a grey to white colour under cloudy conditions). At the air-water interface these two downwelling irradiance streams are either reflected by the water surface (causing sky glint and sun glint) or are refracted as they pass across the air/water interface.

Within the water column similar physical processes of light absorption and scattering are caused by the water itself and its dissolved and particulate constituents. Fluorescence by algal pigments and CDOM may also take place. Backscattered light, either from the substratum passing through the water column upwards or from the water column, may pass across the air/water interface and be observed by airborne or satellite sensors once it has again passed though the atmosphere.

Appendix B contains a primer on the physics of earth observation-based assessment of water quality including a more formal notation for these light transmittance and permutation processes.

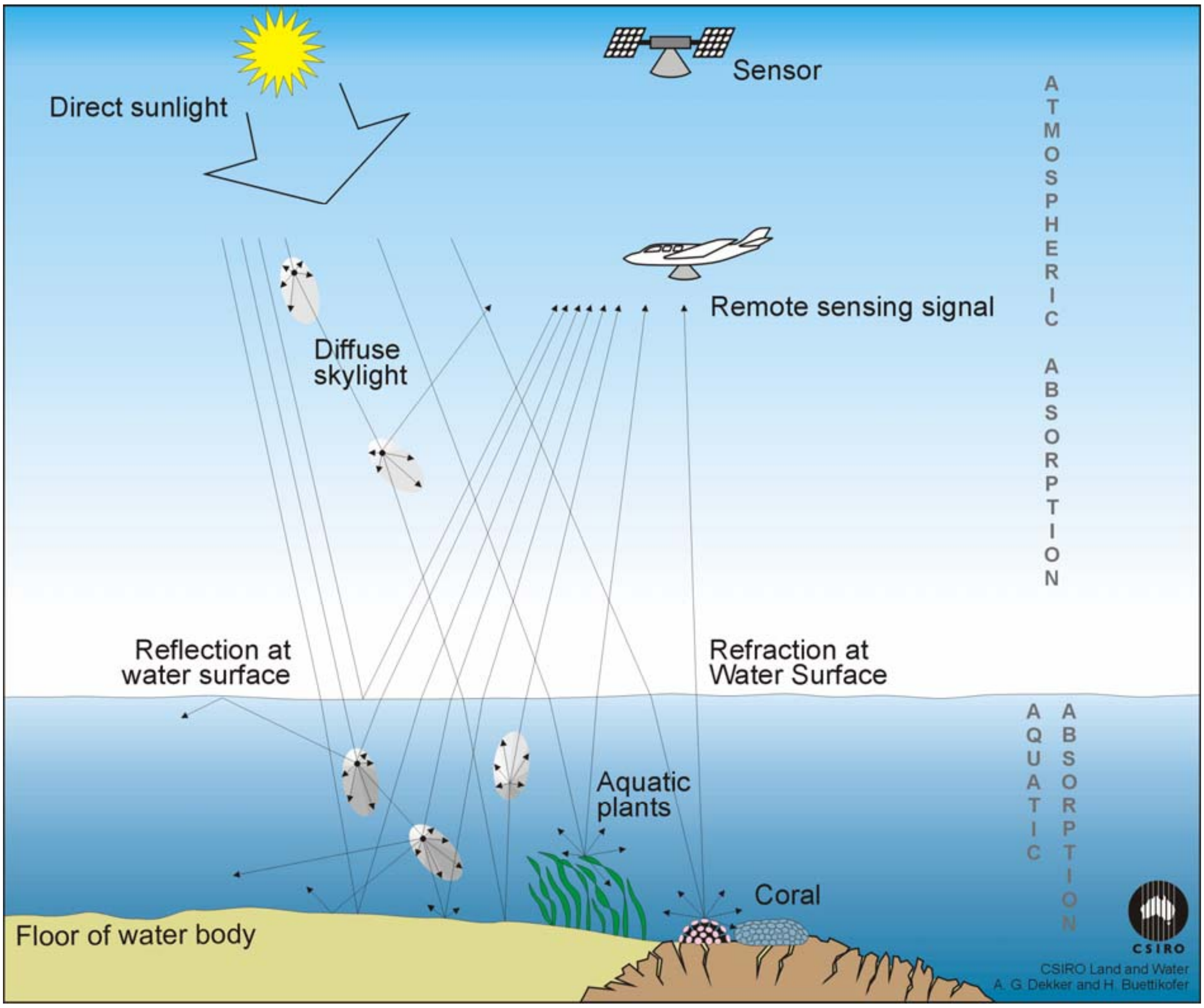


Figure 3-3 Light interactions between the atmosphere, water and substratum

The algorithms for translating the measured spectral reflectance from a water body to water quality variables range from empirical approaches to semi-empirical approaches through to physics-based spectral inversion methods. These approaches are described in the next two sections.

3.8.2 EMPIRICAL AND SEMI-EMPIRICAL ALGORITHMS

Many prior publications focused on empirical approaches relating *in situ* measured samples of water quality variables to radiance or reflectance values measured by a satellite or airborne sensor. These algorithms are based on deriving a statistical relationship between the reflectance measured by a remote sensor and the water column constituent. Although these empirical methods were successful in establishing that water quality could be assessed from space they were seldom implemented operationally as they always required *in situ* measurements to calibrate the relationships for specific water bodies.

Advantages of empirical algorithms are that there is no need to understand the underlying physics such as atmospheric and underwater light processes. However, empirical algorithms struggle when the water column constituent range observed by a remote sensor lies outside of the range upon which the statistical relationship was based, or when other water bodies need to be studied that display different water column constituents such as resuspended bottom material or a different source of CDOM.

Empirical algorithms also do not deal explicitly with atmospheric and water surface (sun and sky glint) issues possibly leading to significant errors in estimated water quality variables. As the satellite archives become longer and older, sensors are replaced by new generations of sensors. The empirical algorithms suffer from the fact that they need to be re-parameterised for each new sensor used.

Semi-empirical algorithms are an improvement over pure empirically-based algorithms as they rely on choosing the most appropriate spectral band or combination of spectral bands to estimate an empirical relationship with the water column constituent. A smart choice of spectral bands used can also partly annul some of the atmospheric and water surface effects. Semi-empirical algorithms, however, also suffer from extrapolation beyond the range of constituents observed and the requirement to establish new semi-empirical algorithms when switching sensors or water bodies.

It is hard for both empirical and semi-empirical algorithms to provide a per pixel level of confidence, in the absence of statistically relevant amounts of *in situ* data across a sufficiently large range of water column concentrations or physical variables for each image analysed. This limits their application in a national monitoring system.

One area where the empirical method has been applied operationally is over the Minnesota lakes in the USA. (Olmanson et al., 2011) presented results for empirical algorithms for Secchi disk transparency and CHL concentrations applied to Landsat data covering 10,500 lakes (larger than 4 ha), 500 lakes for MERIS, 1,250 lakes for MODIS (250 m), 385 lakes for MODIS (500m) and 60 lakes for MODIS (1 km). One reason for this empirical approach being feasible is that a long term, intensive, citizen participation-based *in situ* measurement campaign has been executed. This provided sufficient *in situ* data for regression analysis covering a large range of water column conditions across years and seasons.

Matthews (2011) reviewed most empirical water quality algorithms published and found the following distribution of studies: 50 Europe (incl. Russia), 13 USA, 8 Asia, 1 Africa and none for Australia. The water quality variables retrieved varied from TSM, suspended inorganic matter, CDOM, turbidity, transparency, CHL to CPC. The earth observation sensors varied from ocean-coastal sensors (MODIS, SeaWiFS and MERIS), to Landsat MSS, Landsat TM 4, 5 and 7, ALI, LISS-3, SPOT, ASTER, IKONOS, to the experimental hyperspectral satellites Hyperion, CHRIS-PROBA, and airborne imaging spectrometers such ROSIS, AISA and CASI. No mention was made of how whether any of these algorithms were applied operationally.

3.8.3 PHYSICS BASED REMOTE SENSING ALGORITHMS

The large variation in the concentration of suspended sediments, phytoplankton and coloured dissolved organic matter in many inland waters results in a highly variable light climate.

Due to this optical complexity in these (often relatively turbid) waters, optical models play a key role in understanding and quantifying the effect of water composition on optical variables obtained from either in situ or remote sensing measurements.

The physics-based approach which included bio-optical modelling of the underwater light climate is preferred above (semi-) empirical algorithms.

Many (semi-) empirical algorithms make extreme simplifications about the water composition, such as the (optical) domination of one constituent over all the others.

Dekker et al., 2001. Comparison of remote sensing data, model results and in situ data for TSM in the southern Frisian Lakes. Science of the Total Environment 268(1-3): 197-214.

There is a wide range of forward optical models available for water quality, from generic radiative transfer models (e.g. HYDROLIGHT (Mobley and Sundman, 2000)) to models based on simple analytical solutions developed for specific waters or conditions. These forward models are able to predict the light composition leaving a water body based on the water column constituents and if visible the benthic reflectance.

The mathematical inversion of these analytical models often need some approximations based on modelling or on *in situ* parameterisation and therefore are often called semi-analytical algorithms. They have the important advantage that, due to their relative simplicity, they can be solved very quickly. This is of great importance in an operational remote sensing application where a model must be evaluated at every pixel of an image across thousands of images.

Semi-analytical inversion algorithms are capable of assessing the model based error in the estimation of a water quality variable per pixel. Appendix B.3.6 presents a semi-analytical optical model that describes the main light processes in both clear and turbid waters, without and with bottom visibility, taking into account highly variable optical conditions in the water column and the substrate as well as a complex geometry of the incident light field and the viewing angles of a remote sensor.

Dekker et al., 2001 compared five physics-based inversion methods to a semi-empirical method for estimating bathymetry, water column composition and benthic cover type for a coral reef in the Bahamas and the optically complex Moreton Bay in Australia. The significantly better results for the physics-based inversion method are pertinent to inland waters.

Semi-analytical and radiative transfer–based forward models and semi-analytical or look-up table based spectrum matching inverse models have several advantages for mapping complex water environments, presuming that a remote sensing image has already been corrected for atmospheric and air/water interface effects (Dekker et al., 2006):

1. Repeatability: the method can be applied to multi-temporal images and corrections for changing water column depth (tides) and varying concentrations of water column constituents is possible.
2. Transferability: application of the models to data from a variety of imaging sensors is straightforward.
3. Sensitivity and error analysis can be objectively determined.
4. New knowledge can be added to the simulations and can be retrospectively applied to remote sensing images and archives such as the Landsat TM data archive from 1984 onwards.

3.8.4 PHYSISCS BASED ALGORITHMS IN AUSTRALIA

Physics-based inversion algorithms to estimate all mentioned variables (CHL, CPC, TSM, CDOM, K_d, turbidity and Secchi disk transparency), over rivers, lakes and reservoirs were developed and tested in the mid nineties, mainly using experimental airborne hyperspectral remote sensing sensors with high spectral, spatial and radiometric resolution (Dekker et al., 2001).

In Australia two successful research-demonstration projects using the CASI airborne imaging spectrometer were carried out on the Hawkesbury River (Jupp et al., 1994a) and on Lake Mokoan (Jupp et al., 1994b). These studies demonstrated the feasibility of mapping CHL, CPC, TSM and turbidity for Australian rivers and lakes.

Brando and Dekker, 2003 applied a physics-based inversion method to Hyperion hyperspectral satellite imagery for the complex Moreton Bay waters. This paper demonstrated that it is possible to derive CHL concentration, NAP (as measure of TSM), CDOM and K_d simultaneously from satellite data using a matrix inversion algorithm approach.

Two physics based semi-analytical inversion methods suitable for inland and near coastal waters have been published for Australian applications (Brando and Dekker, 2003; Brando et al., in press; Campbell et al., 2011a; Campbell et al., 2011b), a linear matrix inversion method is applied to Moreton Bay. In Brando et al. (in press) a versatile robust water quality algorithm method: the adaptive Linear Matrix Inversion Method is described. The “adaptiveness” lies in the fact that this algorithm can deal with a significant amount of variation in the concentration-specific (CHL, CDOM, TSM) inherent optical properties of light absorption and light backscattering often occurring in natural waters due to differences in aquatic source material.

The Brando et al. aLMI algorithm has been applied operationally for:

- The Marine Monitoring Program in the Great Barrier Reef, providing knowledge of how material from rivers interacts with oceanic waters
- Regional-specific water quality datasets based on MODIS data for Tasmanian coastal waters

The algorithm is being operationalised on the NCI (through IMOS and e Reefs). Further applications of this algorithm are provided in the case studies in chapter 4. The publications by Campbell & Phinn (2010) and Campbell et al. (2011) related to remote sensing of Queensland reservoirs are based on a similar physics-based adaptive matrix inversion method applied to MERIS data (see 4.2 for examples of Campbell et al.'s approach). The Campbell et al. approach is not currently operational.

For inland waters with bottom visibility the SAMBUCA (Semi-analytical Method for Benthic Unmixing and water Column Concentration Assessment; Brando et al., 2009; Dekker et al., 2011) has been applied to inland waters, estuarine waters, coastal tidal lagoons, coastal waters and coral reefs. Recently another physics-based inversion method was published by Fearns et al., 2011 focusing on retrieving bathymetry over coral reef environments. The Fearns et al. method also explicitly deals with water column constituents and benthic material estimation.

3.8.5 STATUS OF RETRIEVAL ALGORITHMS

Historically the development of algorithms for inland water quality detection has developed from empirical to semi-empirical to semi-analytical. As empirical and semi-empirical algorithms are the easiest to implement and only require routine sampling data from inland water measurements these have been applied most extensively. However, the recent review paper of empirical and semi-empirical algorithms by Matthews et al. (2011) recommend consideration of the underlying physics. They foresee a natural progression to adopting more physics-based algorithms.

Odermatt et al. (2012) reviewed all validated retrieval methods for the period 2006 and 2011. They concluded that (semi)empirical algorithms only function within specific conditions, water bodies and ranges of water variables. Physics-based inversion methods are required to cover all conditions, but validation of these methods needs attention (Odermatt et al., 2012).

From 2003 to 2011 all earth observation of inland and complex coastal water related publications that have been applied to Australian waters are based on the physics-based inversion techniques. The inherent capability of physics-based algorithms to perform per pixel model based confidence assessments means that physics-based algorithms can also be applied to waters that have never been measured before, as the algorithm output for a pixel will determine whether the algorithm is adequately parameterised or not. This provides a non-solution rather than an incorrectly parameterised solution.

As all algorithm approaches to be applied in Australia for water quality assessment will need *in situ* field data and lab analyses of *in situ* samples for either parameterisation or validation of algorithms, it is evident that an effective *in situ* measurement strategy for Australian waters is required. The next section discusses the *in situ* sensors and measurements required for both water quality assessments in general as well as those measurements and instruments specific to supporting remote sensing algorithms development and implementation.

3.9 *In situ* sensors and measurements for assessment and validation

In situ discrete sampling and, increasingly *in situ* high frequency automated sampling are carried out by inland water management authorities operationally in selected waters. Earth observation-based assessments of water quality are not yet operational, but are seen as a valuable additional source of management relevant spatial and temporal water quality information into the future. Each of these three methods has specific strengths and weaknesses as identified in 3.4. This section discusses the potential for merging and adapting *in situ* sampling requirements by water quality management authorities to also start providing parameterisation and validation data for earth observation implementation.

For operationalisation of earth observation for inland water quality three types of *in situ* and laboratory water quality measurements may be of use or are required:

1. Routine *in situ* measurements by water management agencies possibly augmented by some low-cost additions relevant to assessing validity of earth observation derived water quality assessments (Table

3-5). These routine measurements are useful for parameterising (semi)empirical methods as well as for validating all type of earth observation of water quality algorithms.

2. *In situ* high frequency automated sampling above and/or below the water surface that enable frequent match-ups with satellite data as well as provide diurnal variability assessments of the water studied.
3. Expert bio-optical measurements for forward and inverse physics-based retrieval model parameterisation and validation (Table 3-4).

Routine discrete *in situ* measurements of direct relevance for earth observation are CHL concentrations, TSM concentrations (preferably as seston dry weight and then split into organic and inorganic fractions), K_d and Secchi disk transparency. Algal cell identification and counts are of use but need translation into optical observable variables such as CHL light absorption or CPC or CPE absorption. NTU measurements are also of use but again require translation into backscattering of all particulates (including algae) in the water or to K_d.

Increasingly water management authorities are experimenting with, or deploying operationally, *in situ* autonomous high frequency sensor such as algal pigment and CDOM fluorometers. Table 3-5 provides an overview of *in situ* measurements done routinely by water management agencies such as the Office of Water NSW.

In situ high frequency automated sensors are becoming accessible and affordable. These automated sensors often measure variables such as fluorescence by algal pigments or CDOM or in the case of turbidity sensors perpendicular light scattering at one wavelength. *In situ* automated sensors will play an increasing role in validating earth observation derived water quality; as well as assessing natural short term (every few seconds to every few hours) variability; they are more cost-effective than discrete *in situ* sampling. As earth observation images typically provide a spatially explicit snapshot at one time only, *in situ* automated sensors can provide knowledge on short term spatial and temporal variability.

The following tables present the current instrumentation as it exists with CSIRO and with IMOS, as that is the most relevant suite of instrumentation currently deployed for operationalising earth observation for coastal and continental shelf water quality in Australia. The IMOS bio-optical working group is focusing on the autonomous *in situ* sensors as they are deployed on several of the IMOS National Reference Stations as well as on the Lucinda Jetty Coastal Observatory (LJCO). LJCO is designed to validate coastal water quality from earth observation for both Australia and internationally-thus the analogy with similar proposed developments in inland waters is evident. Chapter 5.4.1, Table 5-2 and Table 5-3 section provide the costs associated with these instruments.

Table 3-4 Expert bio-optical forward and inverse model (the physics-based retrieval model) parameterisation measurements

		WATER QUALITY VARIABLES							
		HPLC	SPECTRO-PHOTO	CELL ID & COUNT	LISST-100 [a]	BB9 [a]	AC-S [a]	SD	SPECTRO-RADIO
		LAB-BASED SAMPLE ANALYSIS			*IN SITU* SUBMERGED SUPERVISED				ABOVE/IN WATER
Algal pigment related measurements	CHL	Highly Suited	Highly Suited	Variable has a partial effect	N/A	Variable has a partial effect	Suitable	Variable has a partial effect	Suitable
	CPC	Highly Suited	Suitable	Variable has a partial effect	N/A	Variable has a partial effect	Suitable	Variable has a partial effect	Suitable
	CPE	Highly Suited	Potential	Variable has a partial effect	N/A	Variable has a partial effect	Suitable	Variable has a partial effect	Suitable
	Cell counts	N/A	N/A	Potential	Variable has a partial effect	Variable has a partial effect	Variable has a partial effect	Variable has a partial effect	Suitable
Dissolved organic matter related measurements	CDOM	N/A	Highly Suited	N/A	N/A	N/A	Suitable	Variable has a partial effect	Suitable
Particulate matter related measurements	Particle size distribution	Variable has a partial effect	Variable has a partial effect	Algal cells only	Highly Suited	Suitable	Potential	Variable has a partial effect	Potential
	NAP	N/A	Highly Suited	N/A	Potential	Potential	Potential	Variable has a partial effect	Suitable
	TSM	N/A	Highly Suited	Variable has a partial effect	Potential	Potential	Potential	Variable has a partial effect	Suitable
Light related measurements	K_d	N/A	Calc	Variable has a partial effect	Variable has a partial effect	Variable has a partial effect	Calc	Suitable	Highly Suited
	Turbidity	N/A	Calc	Variable has a partial effect	Variable has a partial effect	Variable has a partial effect	Calc	Suitable	Suitable
	SD	Variable has a partial effect	Calc	Variable has a partial effect	Variable has a partial effect	Variable has a partial effect	Calc	Highly Suited	Suitable

● Highly Suited ● Suitable ● Potential ● Not Suitable ● Variable has a partial effect but cannot be used directly

CHL=chlorophyll; CPC=cyano-phycocyanin; CPE=cyano-phycoerythrin; CDOM =coloured dissolved organic matter; TSM=total suspended matter; NAP = Non-algal particulates; K_d= vertical attenuation of light coefficient; HPLC=high performance liquid chromatography; SD=Secchi disk transparency, Calc=calculated.

[a] Instruments that are currently deployed at the Lucinda Jetty within IMOS context. Other instruments are available from other manufacturers. LISST-100 is a submersible laser scattering instrument that measures concentration and particle size spectra, pressure and temperature. BB9 is a backscatterometer at 9 wavelengths. AC-S is a hyperspectral light absorption and beam attenuation meter. See Figure 5-2 for earth observation processing context.

Table 3-5 Routine *in situ* measurements and recommended autonomous *in situ* sensors for deployment by water management authorities

	WATER QUALITY VARIABLES								
	LAB-BASED SAMPLE ANALYSIS					*IN SITU* SUBMERGED SUPERVISED			ABOVE/IN WATER
	SPECTRO CHL	SPECTRO CDOM	GRAVI-METRIC	FLUORO METERS	CELL ID & COUNT	K_d/ PAR	SINGLE λ LASER NTU	MULTI-λ LASER NTU	SPECTRO-RADIO
CHL	Highly Suited	Not Suitable	Partial effect	Potential	Partial effect	Partial effect	Not Suitable	Not Suitable	Suitable
CPC	Partial effect	Not Suitable	Partial effect	Potential	Partial effect	Partial effect	Not Suitable	Not Suitable	Suitable
CPE	Partial effect	Not Suitable	Partial effect	Potential	Partial effect	Partial effect	Not Suitable	Not Suitable	Partial effect
Algal cell counts	Partial effect	Not Suitable	Partial effect	Not Suitable	Potential	Partial effect	Partial effect	Partial effect	Not Suitable
CDOM	Not Suitable	Highly Suited	Not Suitable	Potential	Not Suitable	Partial effect	Not Suitable	Not Suitable	Suitable
NAP	Not Suitable	Not Suitable	Highly Suited	Not Suitable	Not Suitable	Partial effect	Partial effect	Partial effect	Suitable
TSM	Not Suitable	Not Suitable	Highly Suited	Not Suitable	Not Suitable	Partial effect	Potential	Suitable	Suitable
Particle size distribution	Partial effect	Not Suitable	Not Suitable	Not Suitable	Algal cells only	Partial effect	Potential	Suitable	Suitable
K_d	Partial effect	Partial effect	Partial effect	Not Suitable	Not Suitable	Highly Suited	Potential	Suitable	Suitable
Turbidity (NTU)	Partial effect	Partial effect	Partial effect	Not Suitable	Not Suitable	Suitable	Suitable	Highly Suited	Suitable
Secchi Disk Transparency	Partial effect	Partial effect	Partial effect	Not Suitable	Not Suitable	Suitable	Suitable	Suitable	Suitable

● Highly Suited ● Suitable ● Potential ● Not Suitable ● Variable has a partial effect but cannot be used directly

SPECTRO=spectrophotometric; CHL=chlorophyll; CPC=cyano-phycocyanin; CPE=cyano-phycoerythrin; CDOM =coloured dissolved organic matter; TSM=total suspended matter; NAP = non-algal particulates; K_d= vertical attenuation of light coefficient; HPLC=high performance liquid chromatography; SD=Secchi disk transparency; NTU=nephelometric turbidity units.

3.9.1 NEAR SURFACE REMOTE SENSING

A recent development is the use of near surface remote sensing using above water spectroradiometers that effectively emulate an earth observation signal as measured by an airborne or satellite sensor (albeit the atmospherically corrected earth observation measurements). By implementing these above water *in situ* spectroradiometers several benefits may arise:

- Provide validation or input to atmospheric correction of satellite images.
- Allow the water management authority to apply the same algorithms as used for earth observation imagery in combination with their in situ sampling programs.
- Continuous measurements (under daylight conditions) of a water body.
- Can be mounted on any type of superstructure (bridge, tower etc).
- Do not suffer from biofouling (although they do need cleaning from dust and protection from insects, e.g. spider webs).

Part II Case Studies

4 Case studies

4.1 Introduction

The case studies in this chapter illustrate the feasibility of earth observation for inland water quality, ranging in scale and scope. The chapter commences with studies using the MERIS sensor (Table 3-1), a high temporal, spectral, radiometric and low spatial resolution sensor suited for complex inland and coastal water assessments. The MERIS case studies are presented for the Burdekin (quantitative example) and Murray Rivers (qualitative example).

The next case study uses the medium temporal and spatial, low spectral and radiometric resolution sensor Landsat. GA provided a time series of NBAR-corrected data from September 2008 to January 2010. In addition, examples of the type of images available from Landsat for the Lake Eyre Basin are presented.

Finally, a case study analysing Worldview-2 scenes over Lake Burley Griffin in the ACT is presented as an example of medium temporal and spectral, low radiometric and very high spatial resolution sensor.

4.2 Burdekin Falls Dam-Burdekin River-Great Barrier Reef Lagoon

This case study demonstrates high temporal, high spectral, low spatial resolution MERIS satellite sensor images of the Burdekin-showing a reservoir, river and in the tropics for the December 2010 to March 2011 flood events. This study illustrates the possibilities and limitations of a low spatial resolution (300 m pixel) and high temporal resolution (images one every 2 to 3 days) satellite sensor dedicated to water quality.

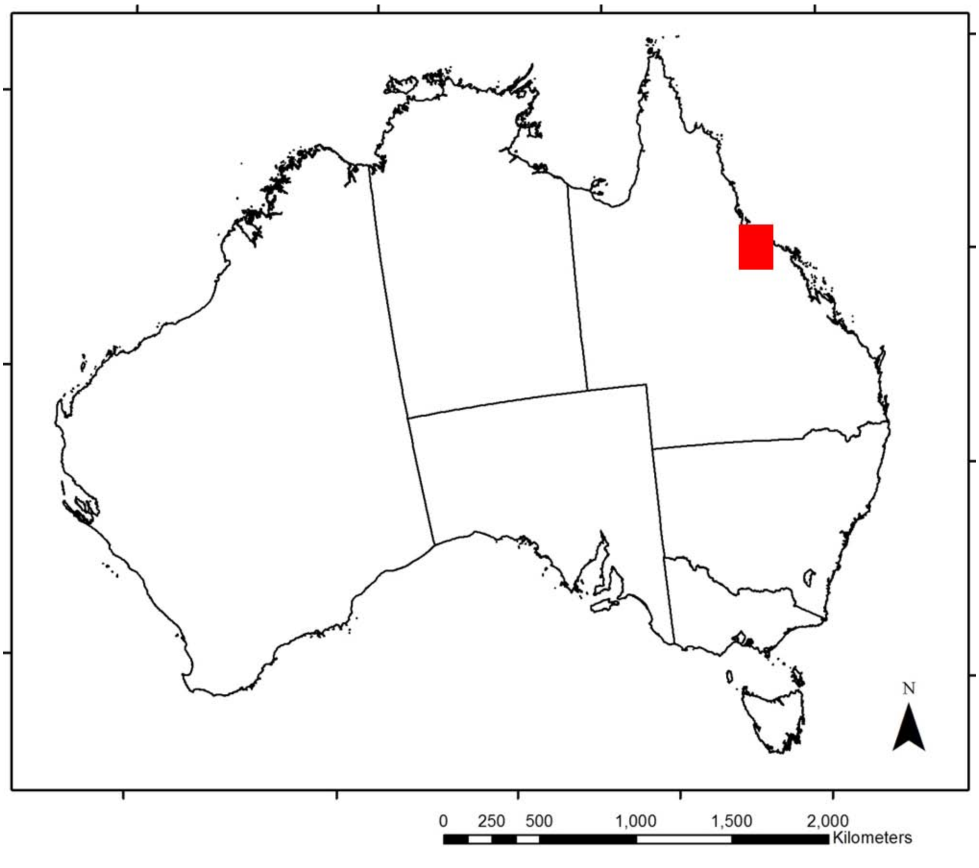


Figure 4-1 Location of the Burdekin Falls Dam-Burdekin River-Great Barrier Reef Lagoon case study

The results are based on the work by Dr Glenn Campbell of the University of Southern Queensland. The method has been published and the results validated for the Burdekin Falls Dam in Queensland in Campbell et al. (2011) for two MERIS images from October 2008 and May 2009. For this case study, Dr. Campbell processed another 4 MERIS images from the period of December 2010 to January 2011, expanding the application of the inland water quality algorithm to include the Burdekin River downstream from the Burdekin Falls Dam as well as to the estuary of the Burdekin River where it flows into the Great Barrier Reef Lagoon.

Figure 4-2, Figure 4-3, and Figure 4-4 show the results for a MERIS image from 16th January 2011, processed using the adaptive physics-based inversion method by Campbell et al. (2011) based on inland water properties for CDOM, CHL and NAP. The CHL values are not presented for the GBR lagoon beyond the estuary as the algorithm was not parameterised properly for marine phytoplankton pigments.

Although there were no independent validation data the results tentatively indicate the algorithm is robust and works for MERIS images (as the estimated concentrations match hydrologic expectations). Campbell also applies a strict criterion to screen any MERIS pixels that may be contaminated by land reflectance. Nevertheless, the processed MERIS images show that there are more than 100 pixels for the Burdekin River downstream of the Burdekin Falls Dam, supporting the finding from the Lower Murray Case study (see further) that with MERIS it is possible to obtain water only pixels in the wider parts of the river. During the time of the MERIS image acquisition, the river was in flood conditions. This provides an example of extreme event monitoring capability of the high temporal frequency MERIS sensor.

Research is needed to assess the validity of the MERIS pixel concentration values calculated for the river floodplain pixels visible in Figure 4-2 through Figure 4-4. These images were processed using inland water optical properties previously determined for the Burdekin Falls Dam. As a large bio-optical dataset is available for the GBR lagoonal waters (Blondeau-Patissier et al., 2009) it may be worthwhile to reprocess these images with the using both land and GBR Lagoon bio-optical properties.

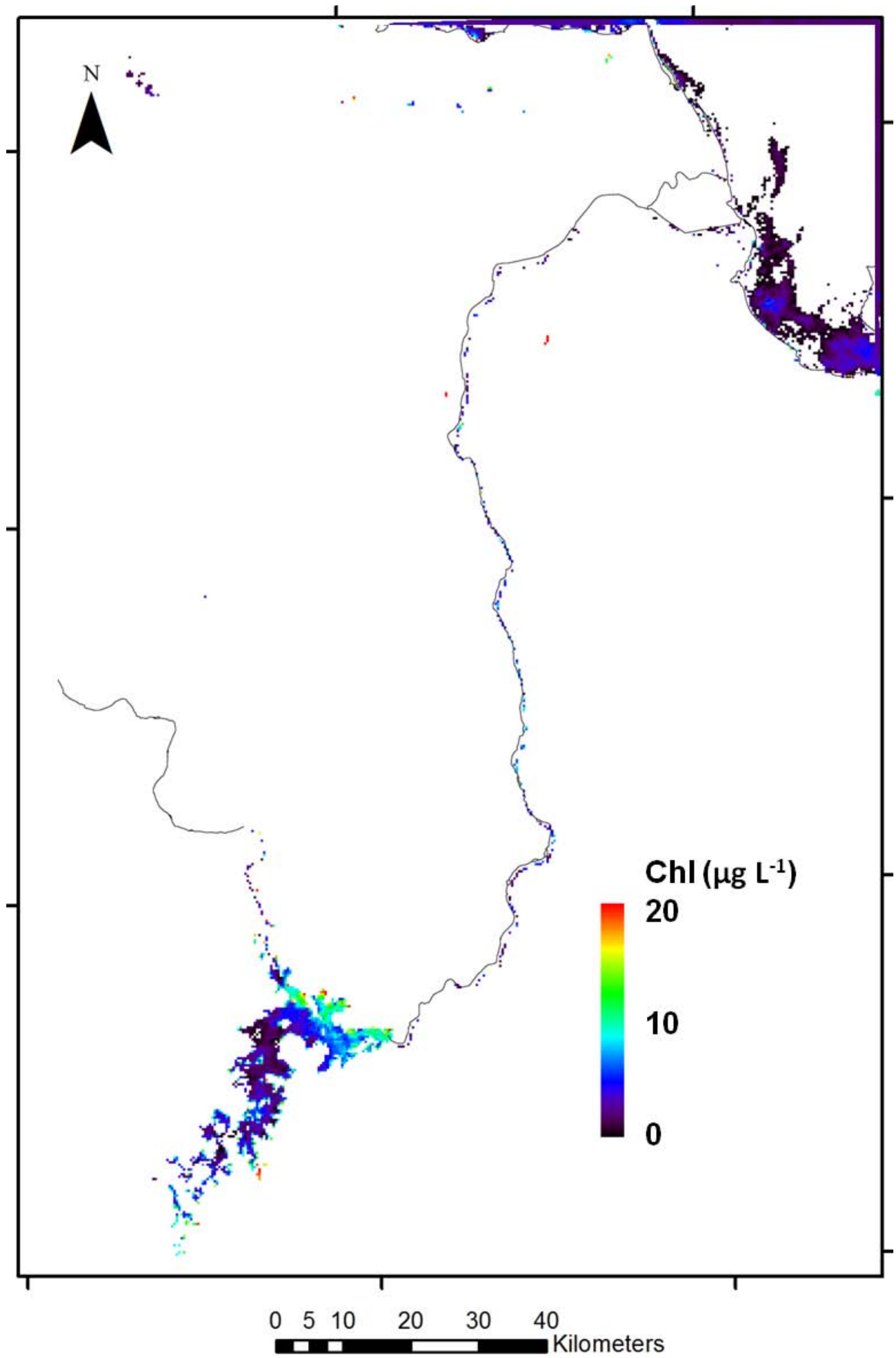


Figure 4-2 Chlorophyll (CHL) in the Burdekin Falls Dam, River and Estuary measured from MERIS

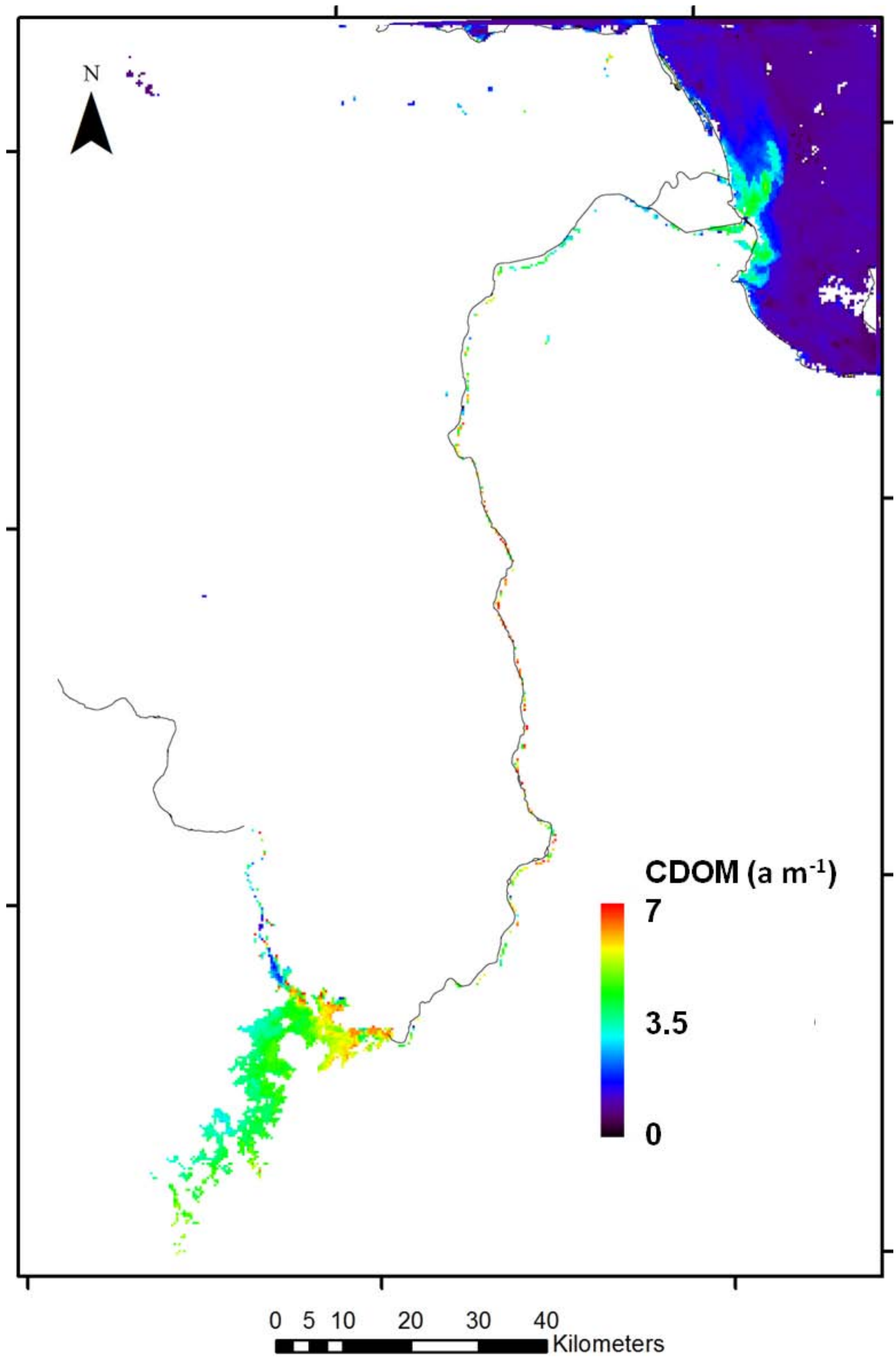


Figure 4-3 Coloured dissolved organic matter (CDOM) in the Burdekin Falls Dam, River and Estuary measured from MERIS

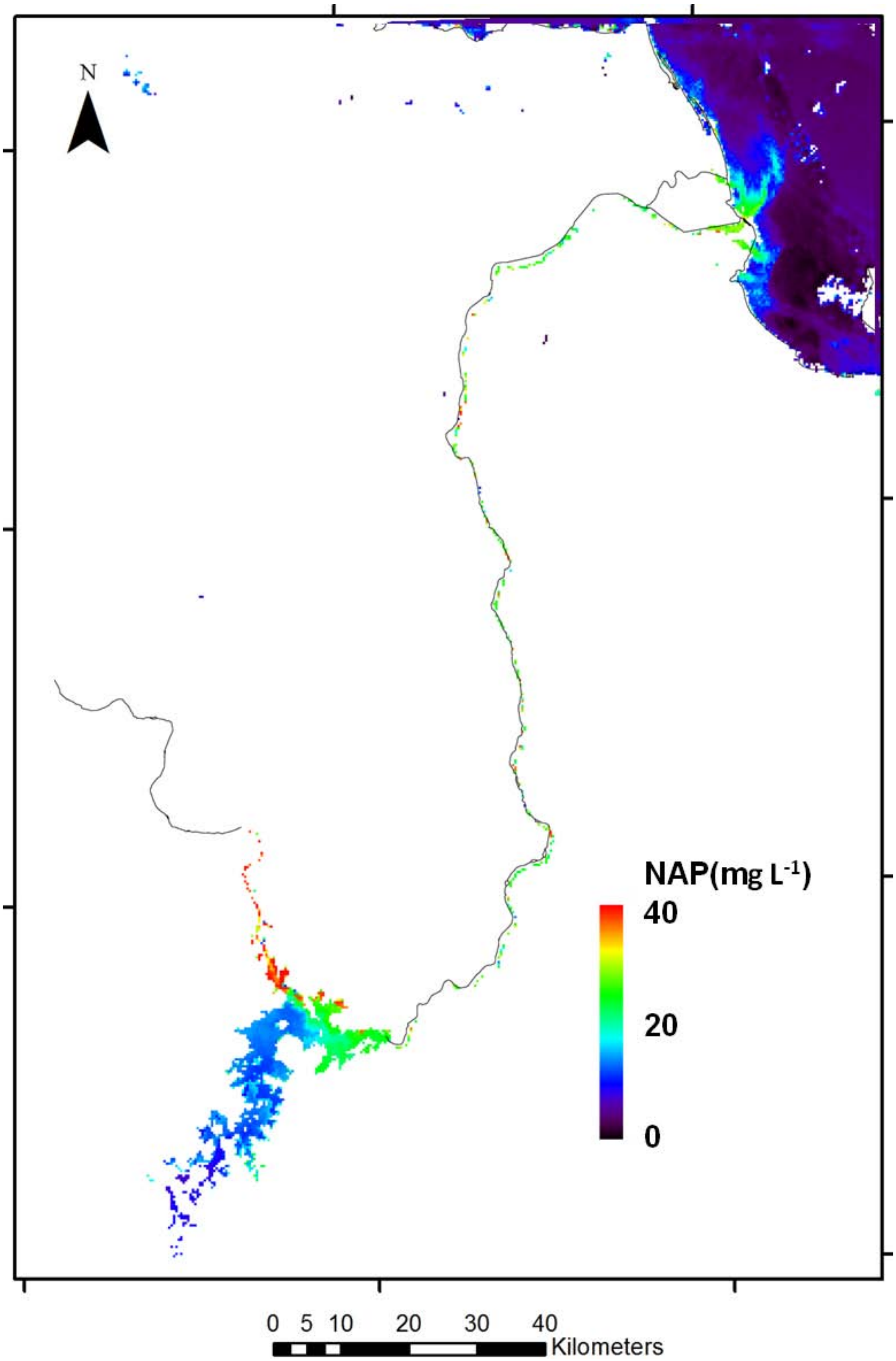


Figure 4-4 Non-algal particulate matter (NAP) in the Burdekin Falls Dam, River and Estuary measured from MERIS

4.3 Murray River: from NSW border to Coorong

This case study provides another example of a MERIS application to a river under flood conditions. This case study used MERIS data from December 2010 to March 2011. The method tested off the shelf image processing software developed for MERIS data by the European Space Agency. CHL was estimated from the MERIS data using the MERIS Case-2 Regional Processor algorithm to derive IOPs such as absorption and scattering and concentrations of TSM and CHL. The algorithm was implemented using the VISAT software processing package in the Basic ENVISAT Toolbox for AASTR and MERIS (BEAM 4.9.0.1). Only water pixels were considered for the analysis.

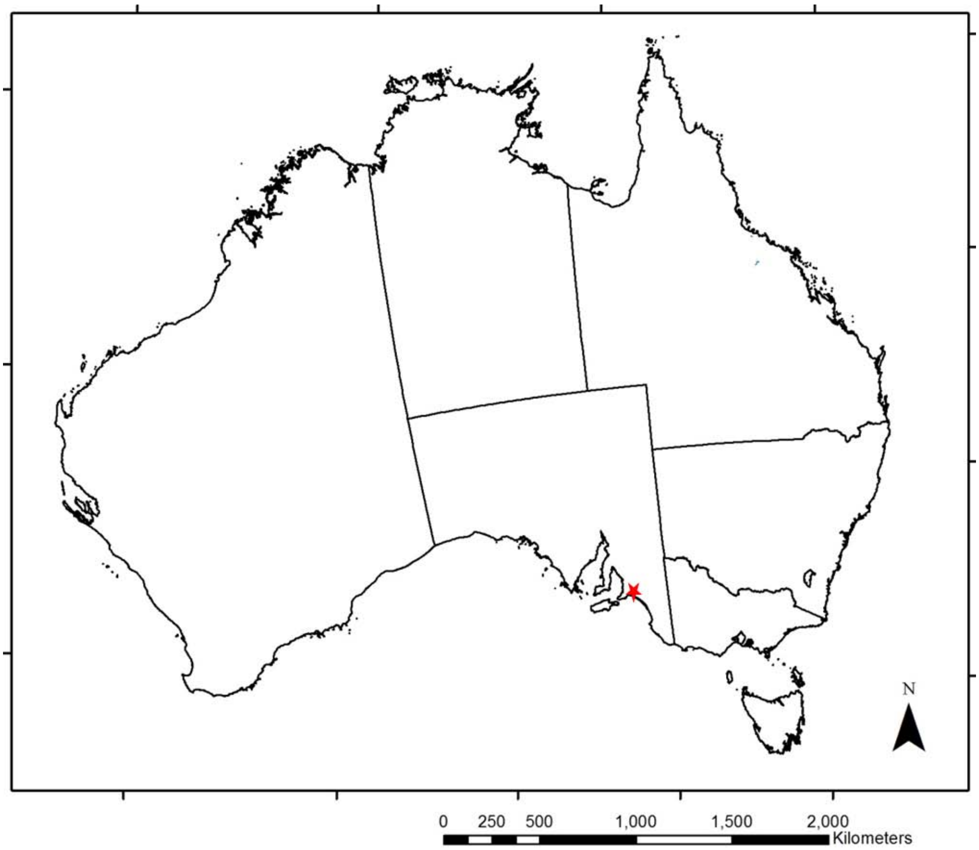


Figure 4-5 Location of the lower Murray case study

Figure 4-6 shows that along the lower Murray under flood conditions there are several locations where the river is broad enough to be imaged with MERIS pixels. In the lower Murray lakes (Alexandria, Albert and Coorong) chlorophyll concentration differences are evident. While the MDBA provided *in situ* datasets for the Murray system, these were only available through early 2010. Thus there was a mismatch between the MERIS data access and the *in situ* data. However, the values measured by the MBDA seem to be in general agreement to those measured from the MERIS imagery. Interestingly, the Coorong shows the expected CHL increase towards the saline southeast, reaching levels of 100 µg l^{-1}, values known to occur regularly (Ford, 2007).

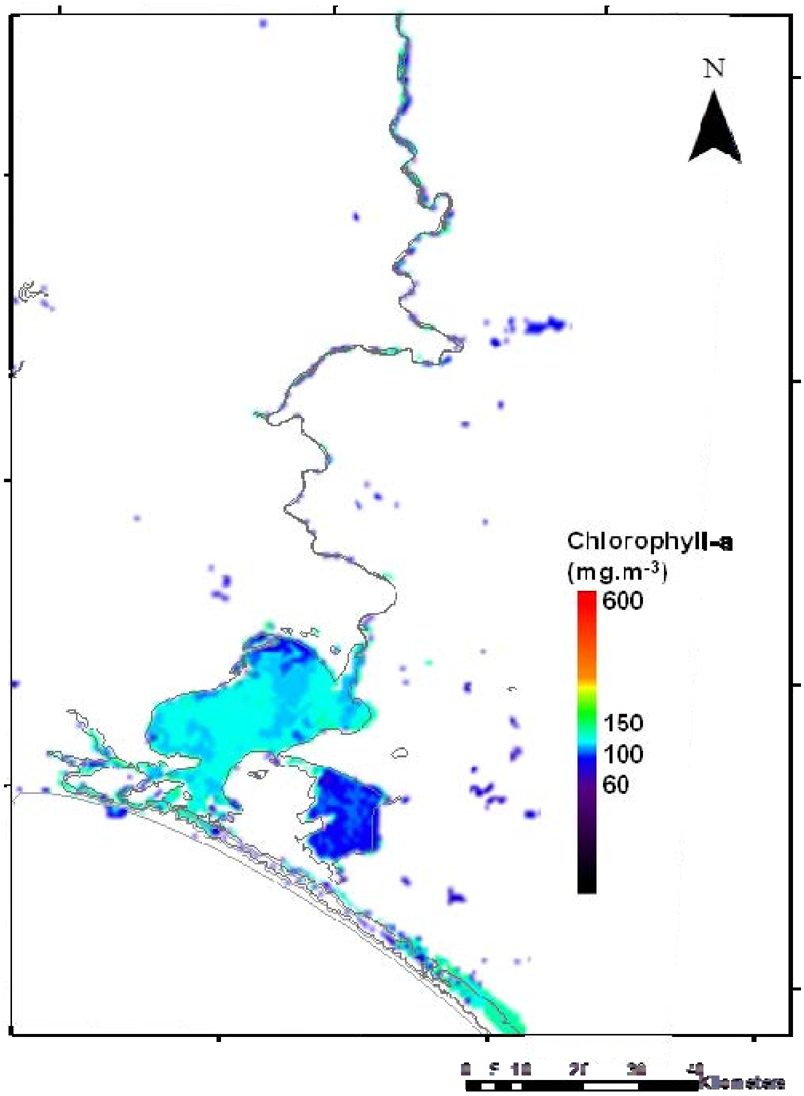


Figure 4-6 Chlorophyll in the lower Murray measured from MERIS

There are approximately 1000 MERIS full resolution images available for the Murray River system from February 2003 to present. Similar to the Burdekin case study, it is likely that this MERIS data can be processed to retrieve water quality estimates provided River Murray bio-optical properties are used to parameterise the model.

4.4 Murrumbidgee River, lakes and reservoirs

This case study focuses on the use of Landsat data for water quality assessment. Landsat is a medium temporal and spatial, low spectral and radiometric resolution sensor designed for land applications. In particular, this case study was used to evaluate the GA's NBAR-corrected Landsat imagery. NBAR correction for Landsat is operationalised at GA.

Briefly, the NBAR correction scheme removes the effects of varying atmospheric conditions, sun-angles and satellite sensor viewing angles and compensates for the effects of these variations on canopies (Li et al., 2010). See Li et al. (2010) for a detailed explanation. The advantage of the NBAR correction scheme is that the user can treat the corrected imagery as an input, where the only processing that is required is to apply operational algorithms to estimate water quality. However, the NBAR correction was designed for terrestrial applications.

GA has invested in operationalising the required pre-processing for the Australian Landsat data series to normalised surface reflectance of terrestrial surfaces, providing NBAR corrected imagery. This investment in pre-processing significantly decreases the infrastructure requirements for operationalisation of Landsat analyses for water quality assessment in Australia.

The NBAR correction was applied to a time series (2008-2010) of Landsat imagery over the Murrumbidgee River area by GA (Figure 4-7). The New South Wales water bodies of sufficient size to provide average water reflectance spectra were: Blowering Reservoir, Corin Dam, Jounama Pondage, Lake Albert, Lake Burrinjuck, Talbingo Reservoir and Wyangala Dam. Additionally, we obtained spectra extracted from NBAR-corrected Landsat data of the ACT from Lake Ginninderra, Lake Tuggeranong, Lake Burley Griffin, Yerrabi Pond and Gungahlin Pond.

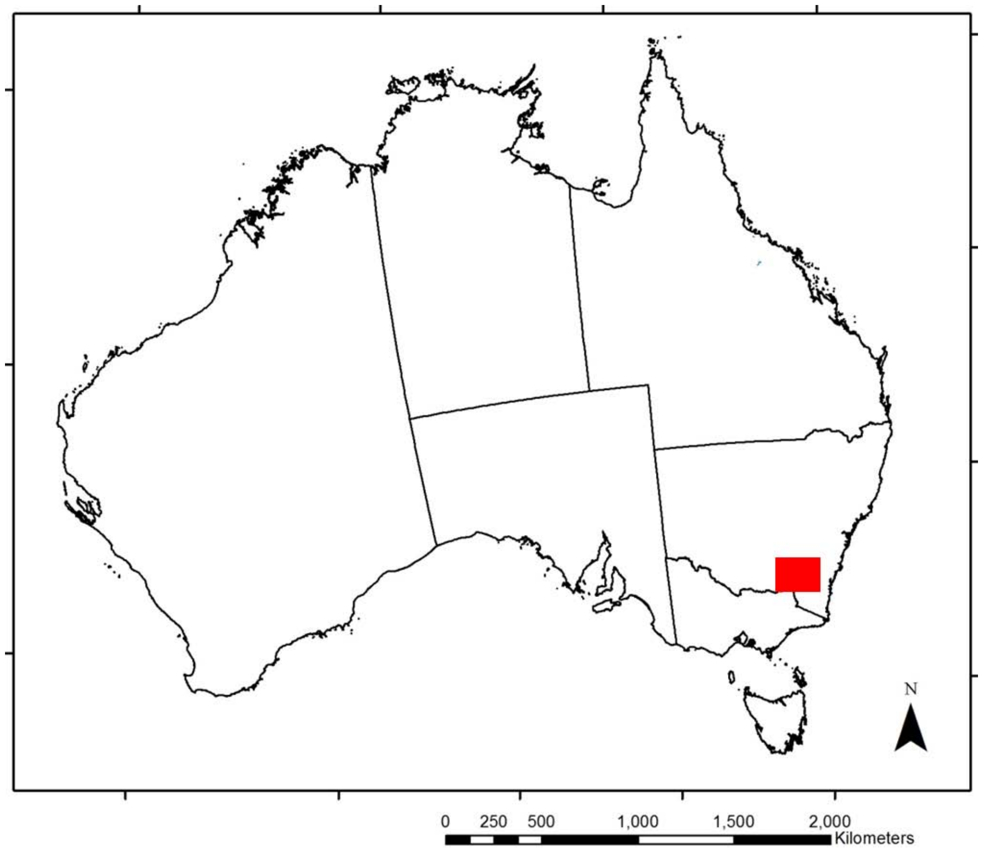


Figure 4-7 Location of the Murrumbidgee catchment water bodies case study

Figure 4-8 depicts the spatially-averaged reflectance over each water body during the time series from 2008-2010 (n=150). The figure illustrates the range of spectral variability of the sampled water bodies.

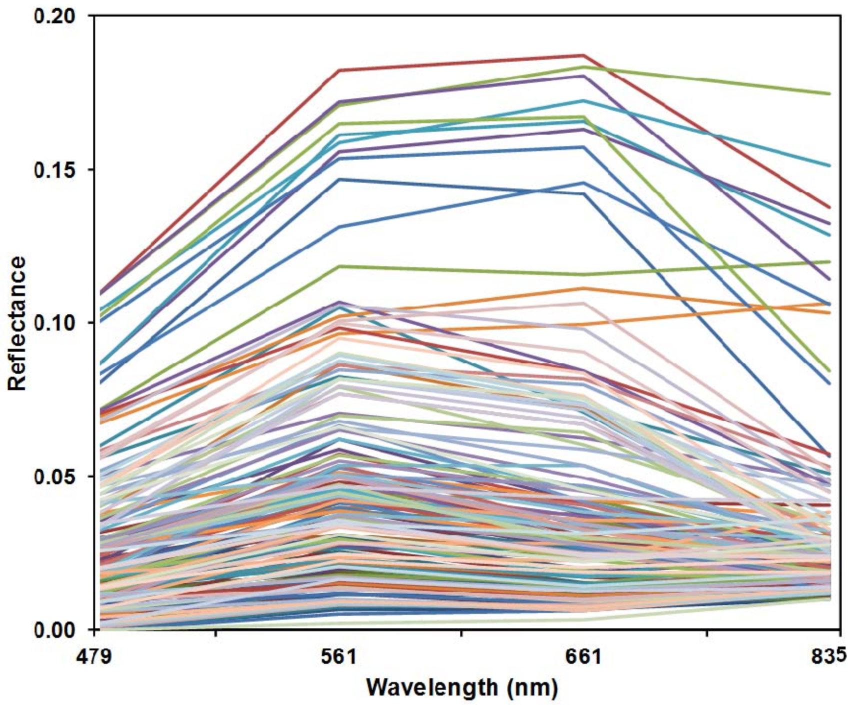


Figure 4-8 Spatially-averaged NBAR-corrected Landsat reflectance spectra for Murrumbidgee water bodies

Water optical properties vary spatially across the Murrumbidgee River area. The optical conditions vary temporally as well. Figure 4-9 shows the variation in the spatially-average surface reflectance spectra for Lake Burrinjuck over time. Figure 4-10 shows some corresponding Landsat images. Note the water colour differences in the six images in Figure 4-10. The top and middle-left images (28 March 2008 and 8 January 2009) show typical surface heterogeneity caused by surface algal blooms.

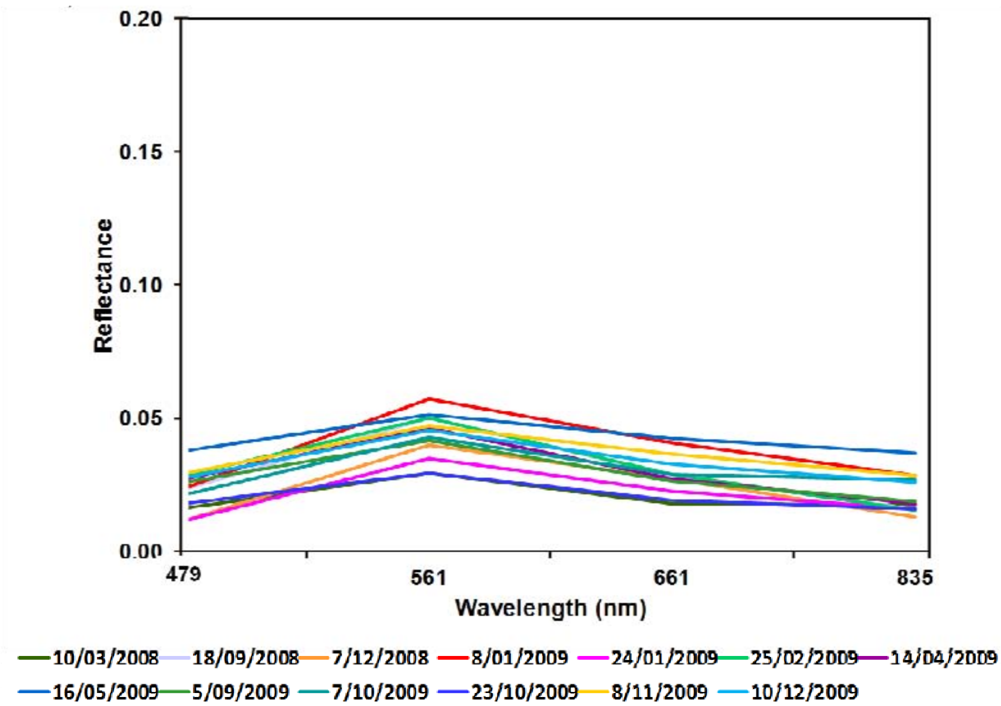


Figure 4-9 Spatially-averaged NBAR-corrected Landsat reflectance spectra for Lake Burrinjuck

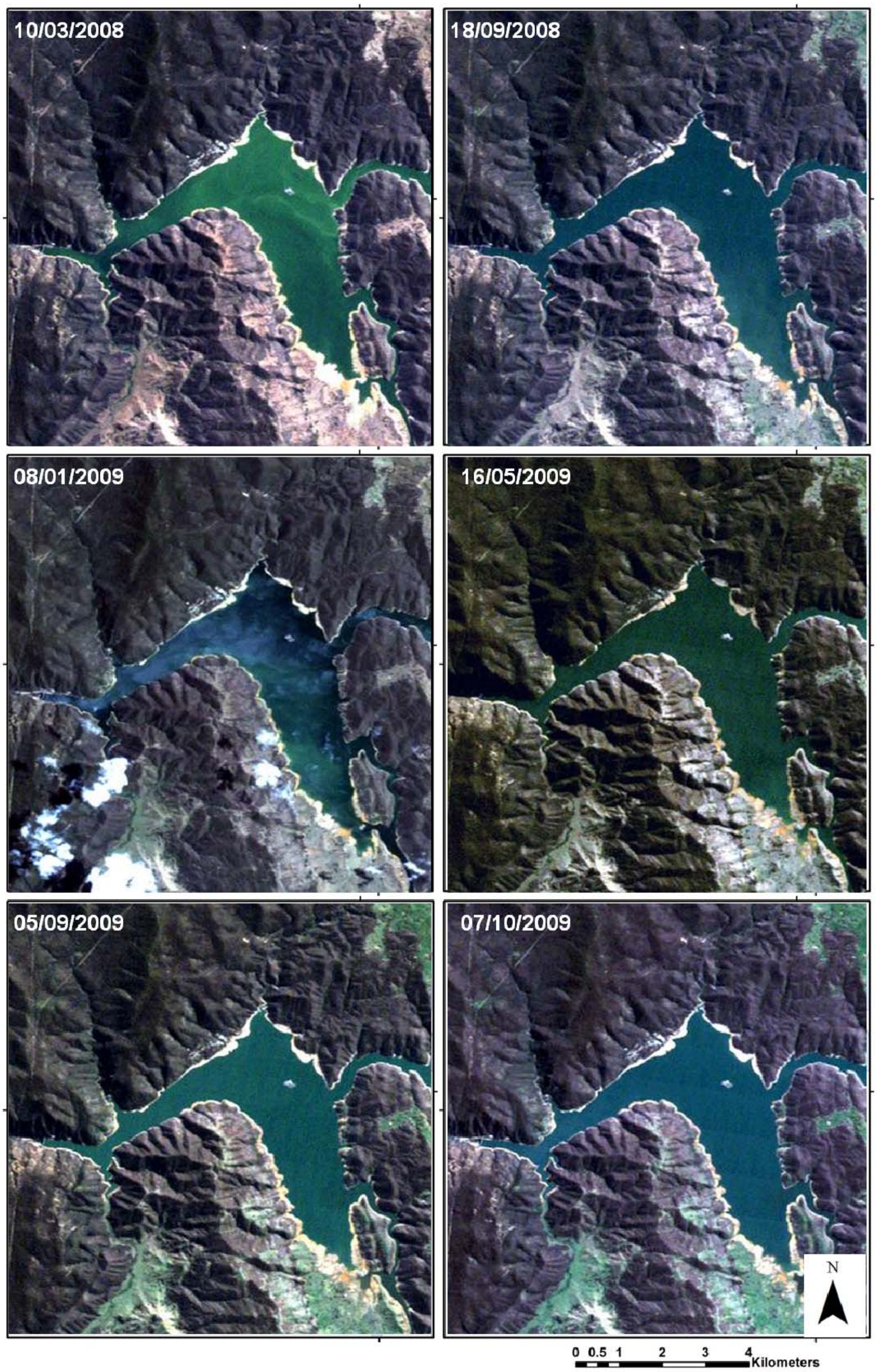


Figure 4-10 NBAR-corrected Landsat imagery over Lake Burrinjuck

The NBAR corrected Landsat images cover September 2008 -January 2010, a period of 16 months. Fourteen Landsat image series covering the entire Murrumbidgee were found of sufficient image quality (generally cloud free and smoke free). This equates to about 40% of images being suitable for further analysis. This is not the maximum amount of Landsat data; it is the minimum amount of data available. For each individual water body more images may be available. Thus, a sensor system such as Landsat provides approximately monthly cover for this area, though the average distribution of temporal cover across seasons is skewed towards clear weather conditions.

CSIRO's adaptive - Linear Matrix Inversion (aLMI) algorithm (Brando et al., in press) was adapted to Landsat spectral bands. The algorithm was parameterised using Lake Burley Griffin specific inherent optical properties from January-March 2010. These were used as proxy parameterisation because they were the only dataset available for the region. The algorithm was then applied to the NBAR-corrected Landsat spectra.

Table 4-1 Results of aLMI algorithm applied to NBAR-corrected Landsat spectra of Murrumbidgee water bodies

	CHL (µg/L)	CDOM (a/m)	NAP (mg/L)
Median	11.2	0.5	7.3
Average	30.6	0.8	45.7
Min	0.7	0.0	0.6
Max	213	6.7	45.7

To validate these water quality products we requested in situ water quality information from the MDBA and the NSW Office of Water. From both agencies it was clear that, despite their best efforts, the data were limited in duration and location. The most suitable data available was measured in the Murrumbidgee at Wagga Wagga. It was assumed this measurement station was representative of the Murrumbidgee water body region. The most available measurements were NTU measurements for which we derived a conversion factor for NTU to TSM:

TSM = 0.7373 (NTU) + 9.6685. R2 = 0.80, N=50 (out of 153 spectra).

The conversion made it possible to perform the comparisons given in Figure 4-12, where the algorithm results and the *in situ* measurements of NTU recalculated to TSM are displayed.

The results show overall agreement between the *in situ* measurements and the Landsat satellite data-derived measurements. There is an approximate relationship of TSM= 1.8 * NAP in these results. This may be due to the NAP (non algal particulates) missing the chlorophyll contents (as NAP + chlorophyll = TSS) as well as being due to the measurement methodology between TSM and NAP being different (different filter sizes and different manners of sample preparation).

In the Murrumbidgee Landsat data series from 2008-2010 only 34 % of the NBAR-corrected reflectance spectra led to water quality concentration values. The remaining spectra, when processed using the aLMI algorithm, returned too large errors via the aLMI in built error estimate function. This is due to two reasons: either the NBAR correction is not accurate enough in all cases to provide reliable surface reflectance spectra or the bio-optical parameterisation (making use of the Lake Burley Griffin measurements of summer 2010) are not representative of the waters encountered in these two years of Landsat images across the entire Murrumbidgee.

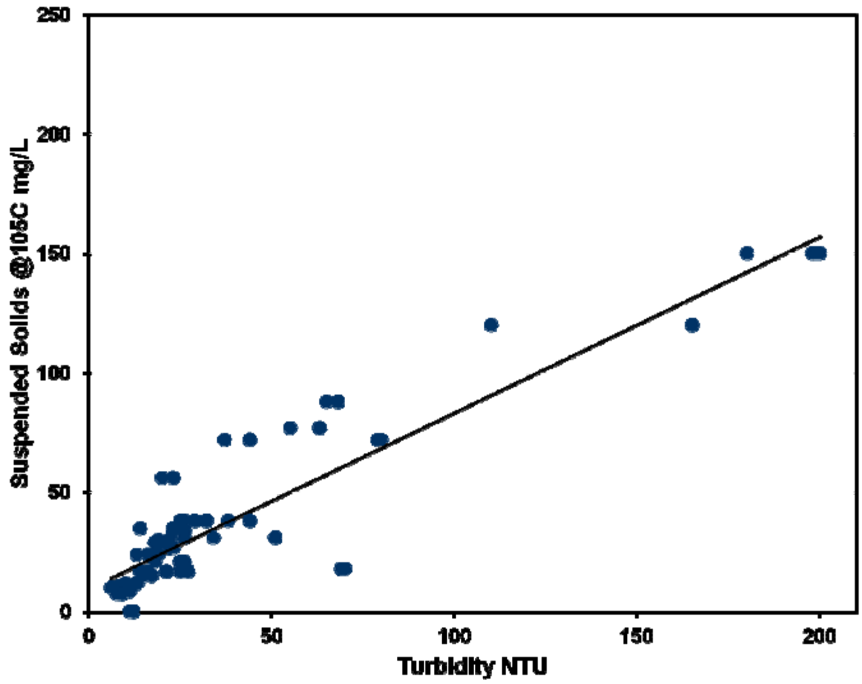


Figure 4-11 Total suspended matter measured as suspended solids versus turbidity

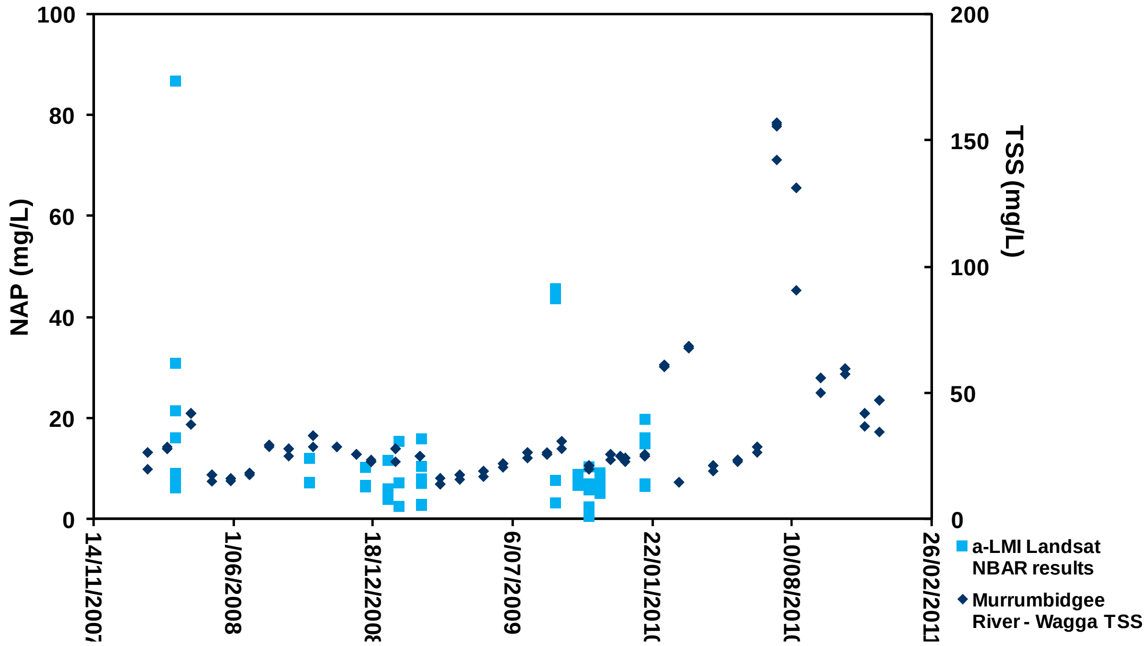


Figure 4-12 Landsat derived NAP concentration in Murrumbidgee area lakes and TSM for Murrumbidgee River near Wagga

4.5 The January 2011 Victoria black water flood event

During January 2011 the Avoca, Campaspe and Loddon River catchments in Victoria underwent severe flooding, leading to Kerang being cut of entirely at one stage. Figure 4-14 and Figure 4-15 show a pre-flooding image and flood image of the Avoca, Loddon and Campaspe rivers in Victoria. Although it was out of the scope of this study to quantitatively analyse the information contained in these images it is clear that earth observation imagery can capture extreme events. The figures also show the transformation in many of the (often shallow and sometimes saline) lakes in this area from light coloured to black water affected. All the black areas in figure 4-15 are inundated areas.

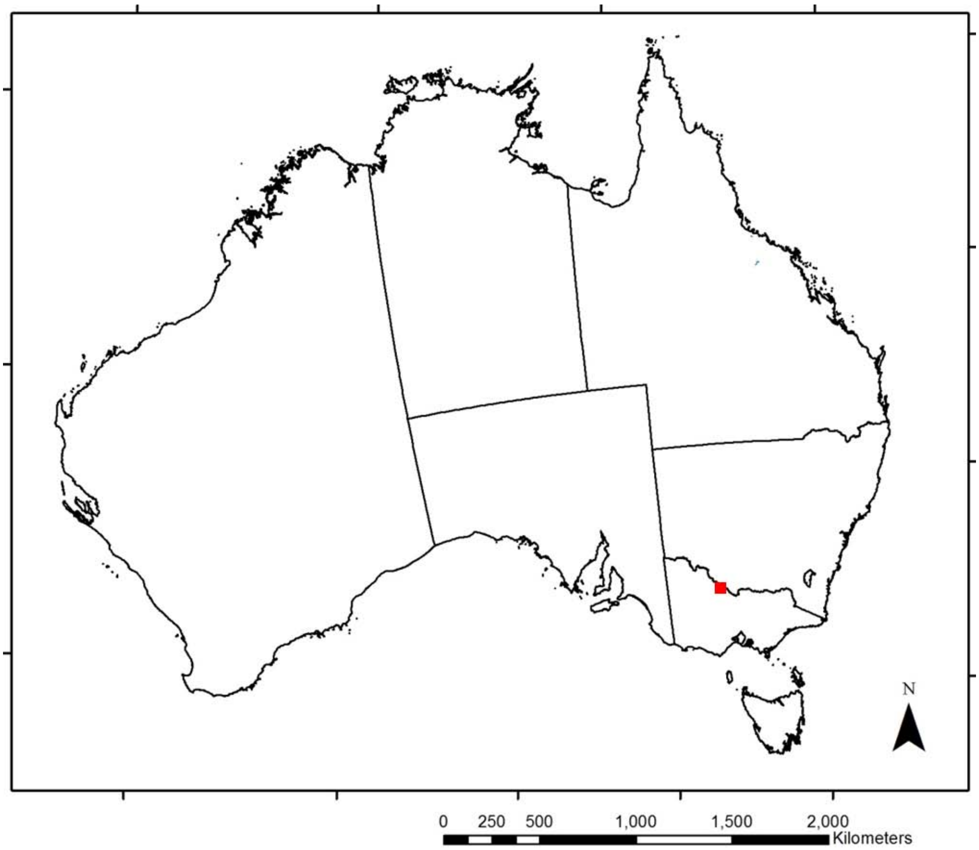


Figure 4-13 Location of the Victoria black water event case study

Once inversion algorithms are properly parameterised for the high organic matter content in water types that occur during these black water events, it will be possible to provide information about the water quality of such extreme events. This information may provide understanding of the amount of carbon transported by these events. However, more research is needed.

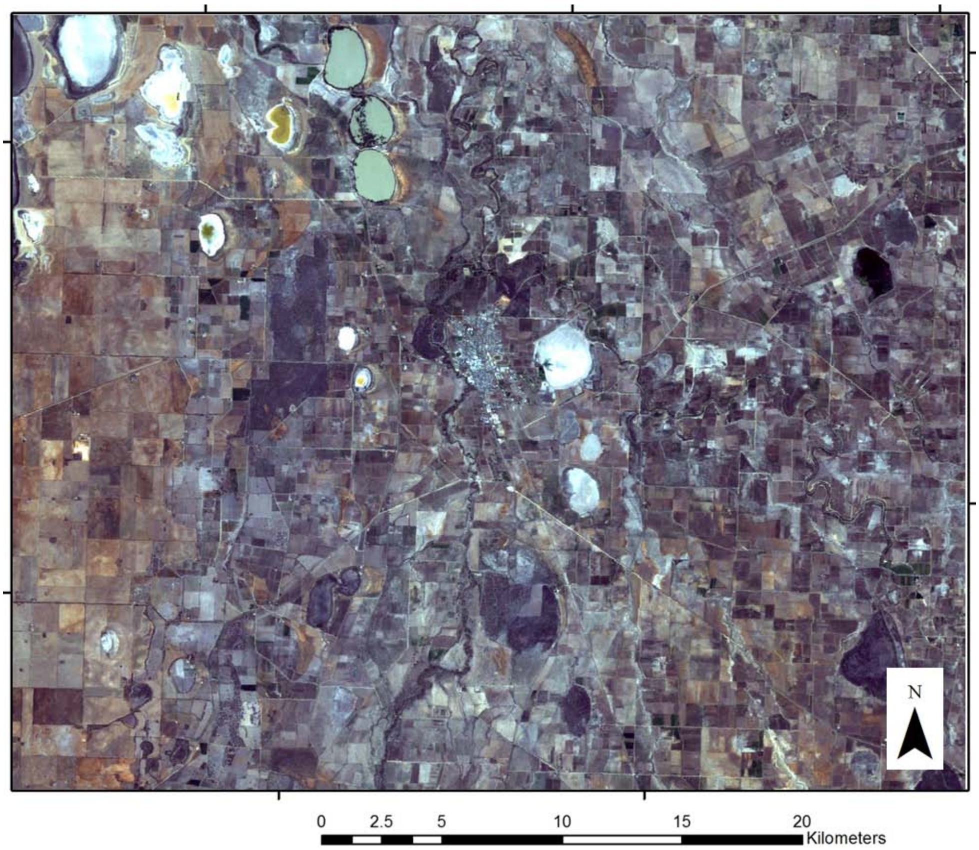


Figure 4-14 Landsat image of the Kerang area in Victoria 16 December 2009

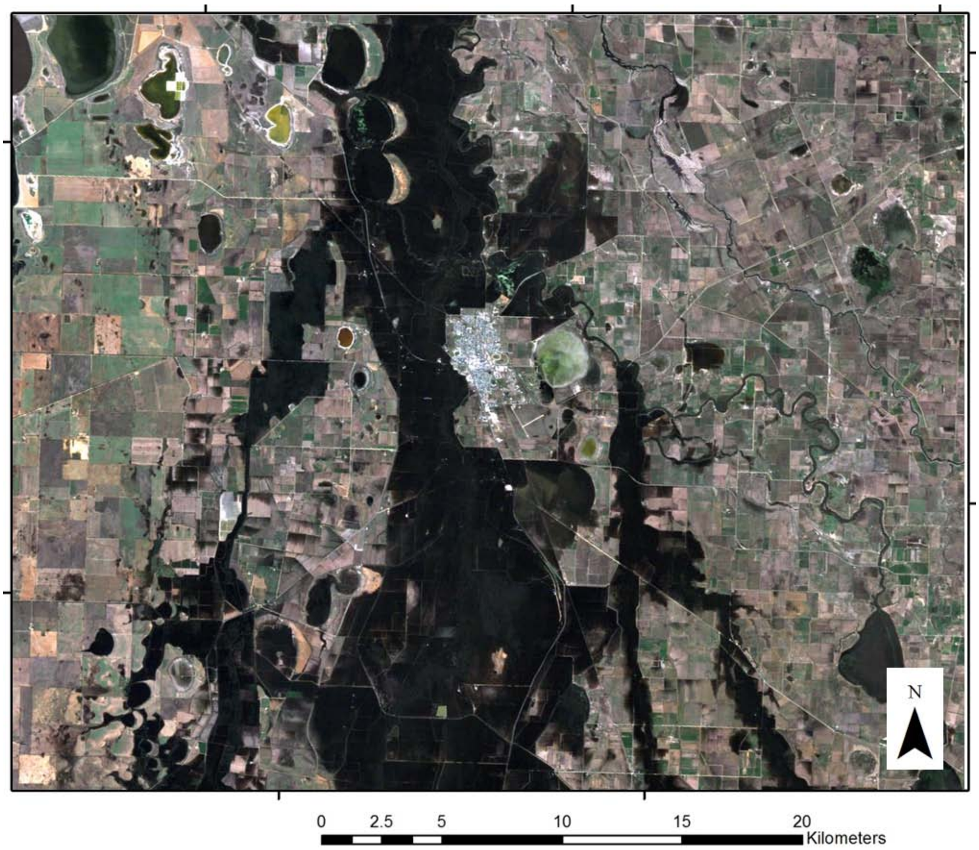


Figure 4-15 Landsat image of the black water flood surrounding Kerang in Victoria 20 January 2011

4.6 Lake Eyre Basin rivers and lakes

The Lake Eyre Basin Agreement (http://www.lebmf.gov.au/) establishes a cooperative framework for the Commonwealth, Northern Territory, Queensland and South Australian Governments to jointly address issues about the management of water and related natural resources of the cross-border rivers within the Lake Eyre Basin Agreement Area. The Agreement recognises the ecological importance of the Lake Eyre Basin as well as its social and economic values. The Lake Eyre Basin Ministerial Forum is required to review the condition of all watercourses and catchments within the Lake Eyre Basin Agreement Area. The rivers in the Lake Eyre Basin are generally considered by governments and the community to be in relatively good condition, and are amongst the last unaltered dryland river systems in the world. However, knowledge of the ecology of these arid rivers and their catchments is limited and not uniform across the Basin.

Methodologies and techniques used to assess other river systems are not necessarily applicable or appropriate for the Lake Eyre Basin rivers and catchments. The vastness and extreme flow variability of arid rivers means that a broad-scale and long-term approach is required to understand how these systems work. Recent scientific projects have also identified many gaps in our knowledge of the dynamics of arid rivers and the kinds of information required to assess and maintain their health.

In the 2011 Lake Eyre Basin Rivers Assessment Project Plan specific attention is paid to hydrology, fish and water quality. For the purpose of this study GA provided some NBAR-corrected Landsat images of Lake Eyre in order to assess whether the CSIRO aLMI algorithm would be able to determine water quality (Figure 4-17 and Figure 4-18).

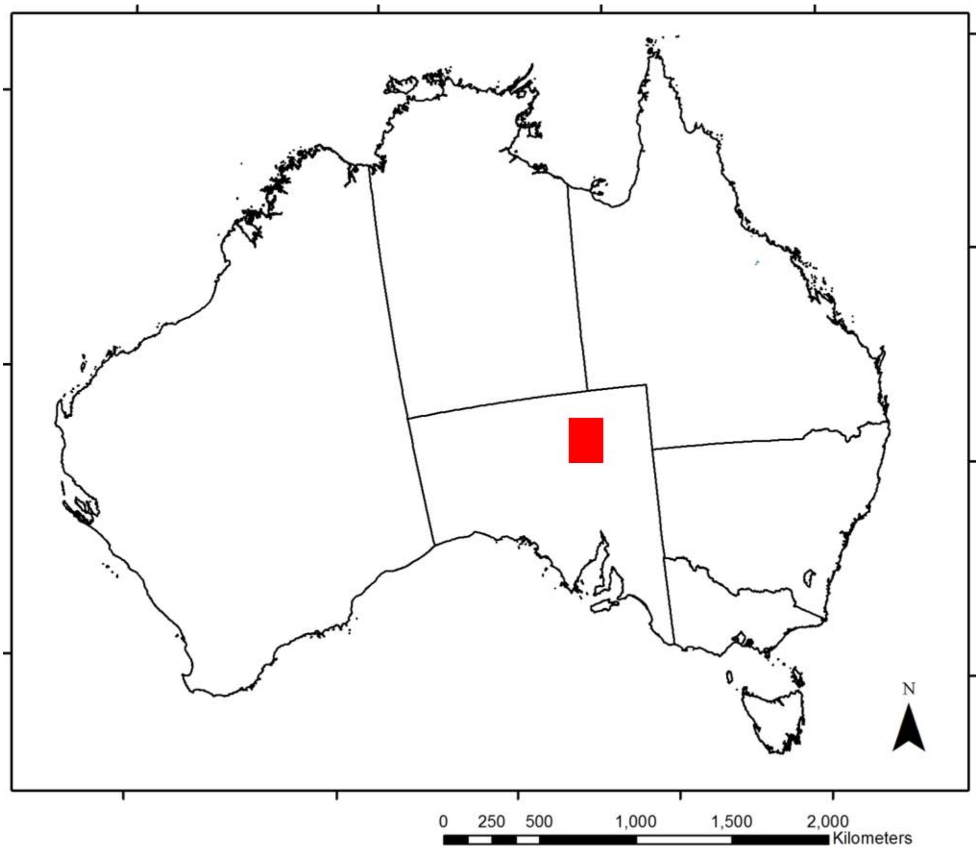


Figure 4-16 Location of the Lake Eyre case study

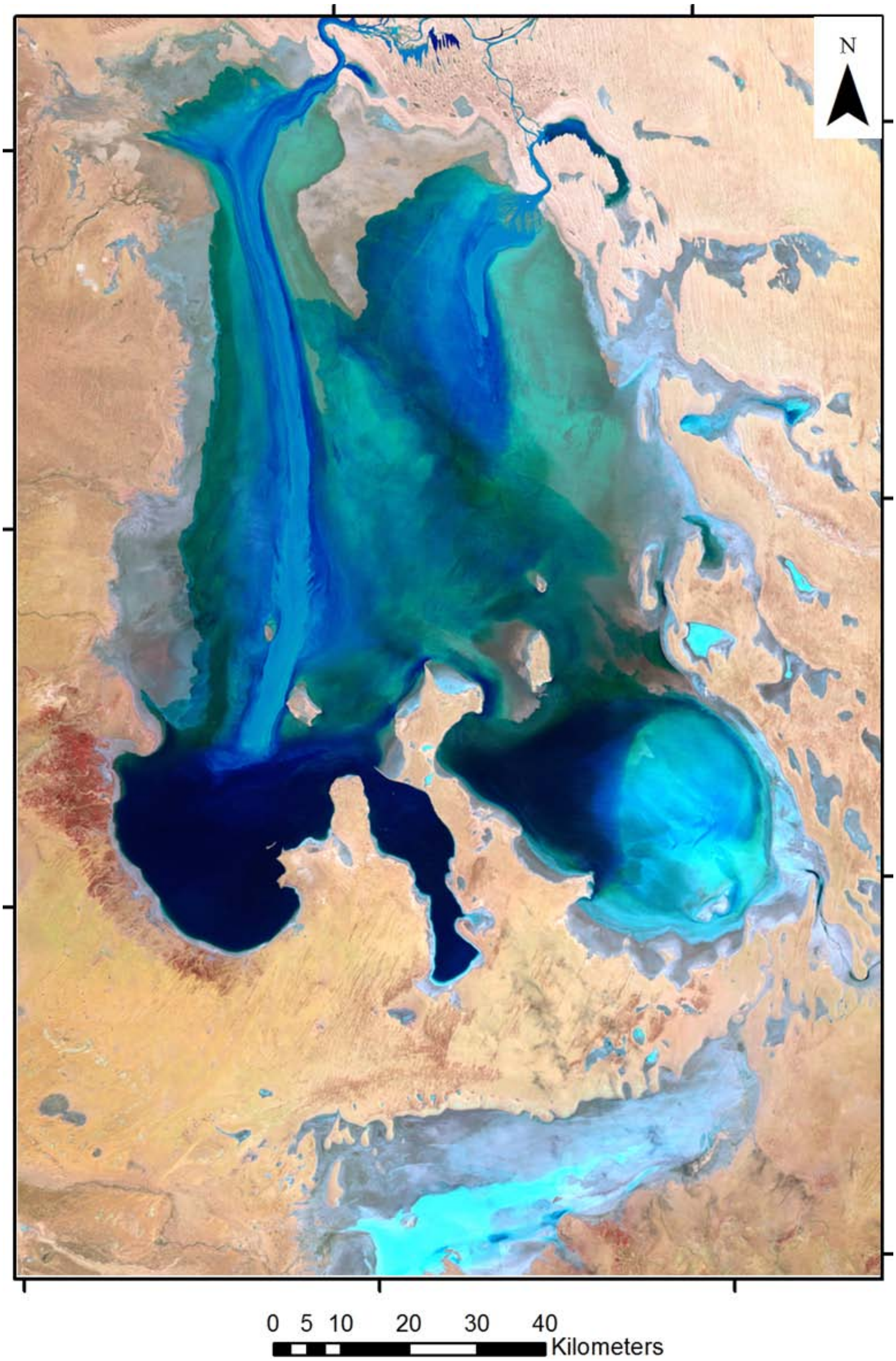


Figure 4-17 Landsat image of Lake Eyre, 9 May 2009 after flows from the 2008-2009 wet season

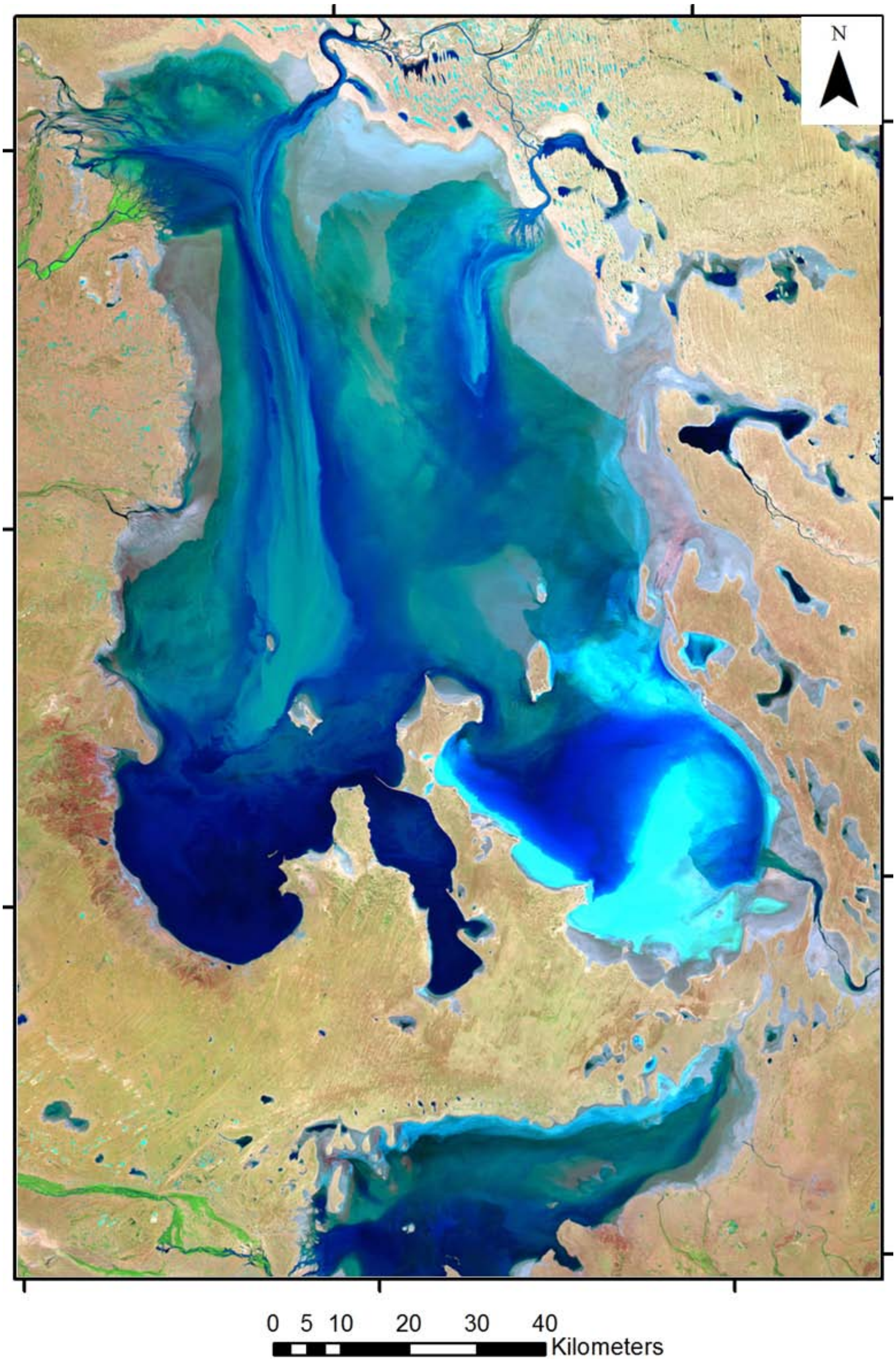


Figure 4-18 Landsat image of Lake Eyre, 28 March 2011 after significant flows during the 2010-2011 wet season

In this case the results did not produce any results as the aLMI algorithm in built error assessment algorithm considered it impossible to find a match between these measured spectra and the modelled spectra from the aLMI algorithm. The bio-optical properties of the waters in Lake Eyre are so different from the existing parameterisation that dedicated bio-optical fieldwork would be necessary to parameterize the aLMI model with the correct bio-optical properties. Another possibility is that the NBAR correction is not sufficiently accurate for estimating correct water reflectance spectra.

4.7 Lake Burley Griffin using WorldView-2 and Landsat

For Lake Burley Griffin in the Australian Capital Territory it was possible to provide case study results for both Landsat and WorldView-2 satellite imagery. WorldView-2 (launched in 2009) is an example of sophisticated commercial high spatial resolution imaging systems. Worldview-2 has programmable (on demand) temporal resolution, and medium spectral and radiometric resolution. The combination of eight spectral bands covering the blue to nearby infrared wavelengths and the high spatial resolution of 2 m pixels makes this sensor unique; it has double the number of spectral bands in the visible and nearby infrared compared to all other high to medium spatial resolution sensors (Table 3-1) creating higher reliability and the ability to better discriminate chlorophyll from blue green algal pigments, suspended matter and coloured dissolved organic matter and vertical attenuation of light (and related NTU and transparency) maps.

CSIRO Land & Water and SKM have collaborated since 2010 to provide demonstration type water quality products from WorldView-2. CSIRO Land & Water performed fieldwork and laboratory studies during January 2010-March 2010. SKM (supported by Digital Globe) provided 20 WorldView-2 image collections. Here we present results of several dates where good Worldview-2 data was available with corresponding relevant *in situ* data.

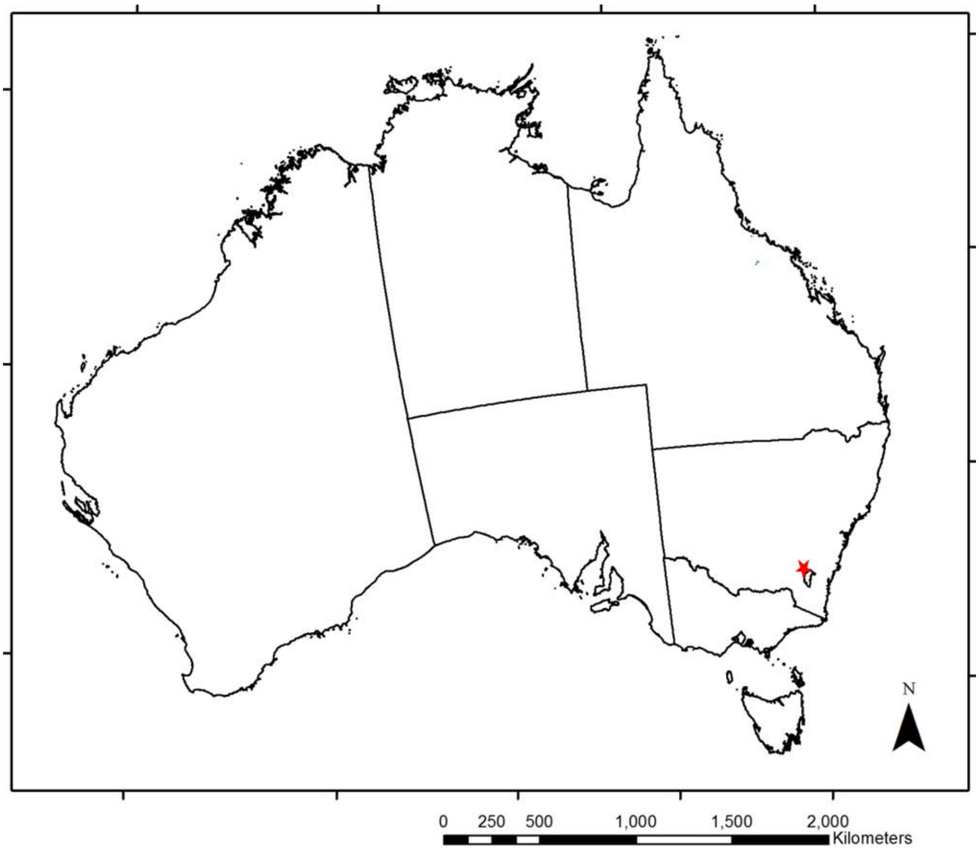


Figure 4-19 Location of the Lake Burley Griffin case study

The CSIRO aLMI algorithm was adapted to process the Worldview-2 spectral bands. Parameterisation was performed using ten *in situ* bio-optical datasets measured in January and March 2010 field campaigns. The atmospheric correction was performed using the CSIRO c-WOMBAT-c (MODTRAN based) atmospheric correction program.

We also present an experimental blue green algal map of Lake Burley Griffin using a semi-empirical algorithm. It is possible to adapt the aLMI algorithm to also include assessment of blue green algal pigments; however, that implementation fell outside the scope of this feasibility study.

Because we also had access to the NBAR-corrected Landsat imagery for Lake Burley Griffin (see Figure 4-28) and were able to apply the aLMI algorithm, it was possible to compare the National Capital Authority and

CSIRO Land & Water *in situ* measurements, the NBAR-corrected aLMI processed Landsat data and the c-WOMBAT-c and the aLMI processed Worldview-2 data.

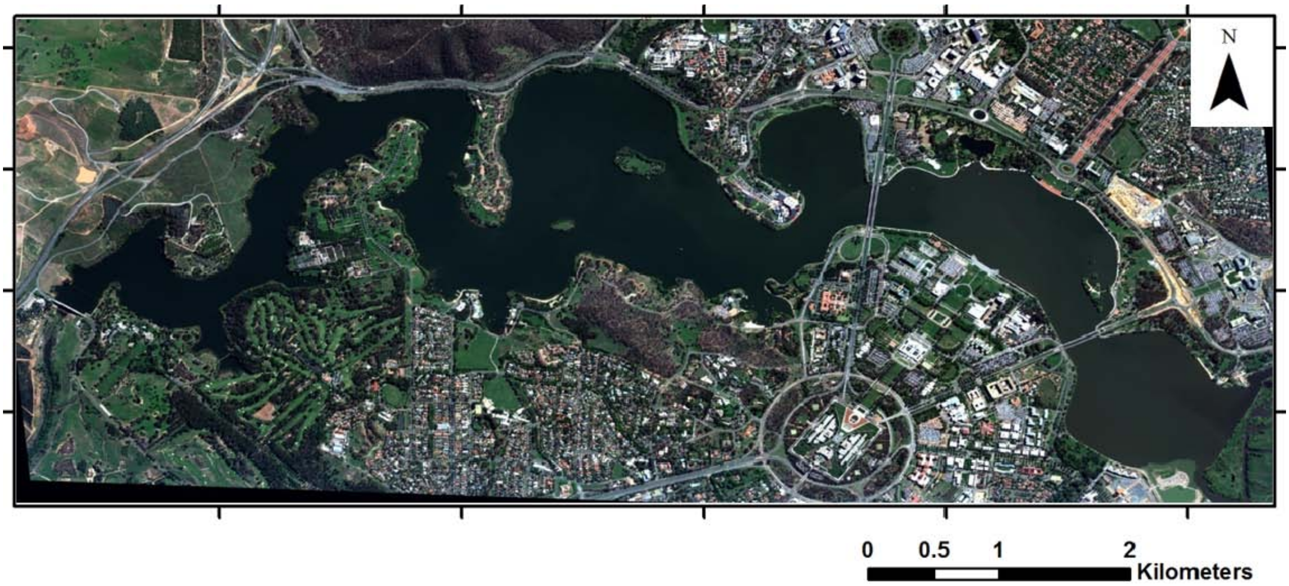


Figure 4-20 Worldview-2 image of Lake Burley Griffin 17 March 2010

Figure 4-20 shows a WorldView-2 two meter spatial resolution image of Lake Burley Griffin on 17 March 2010. Figure 4-21, Figure 4-22 and Figure 4-23 show the results of applying the aLMI algorithm to this image producing maps of CHL, NAP and CDOM. Some sensor noise and striping indicative of the relatively low radiometric resolution is visible in these images.

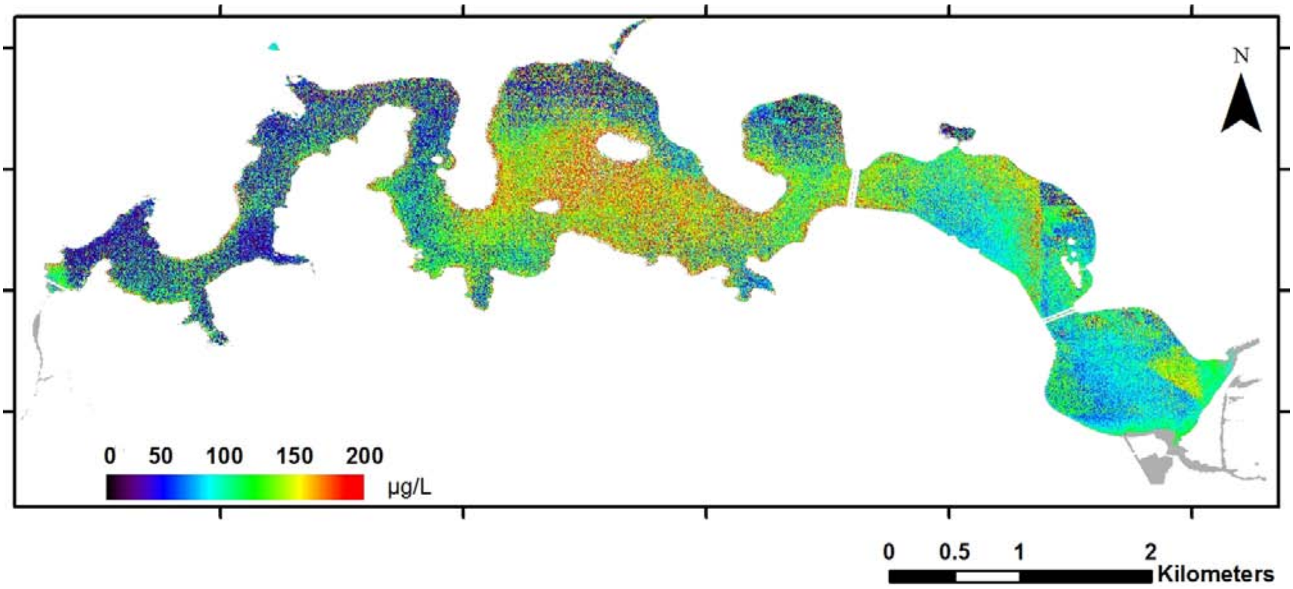


Figure 4-21 Chlorophyll concentration in Lake Burley Griffin from a Worldview-2 image 17 March 2010

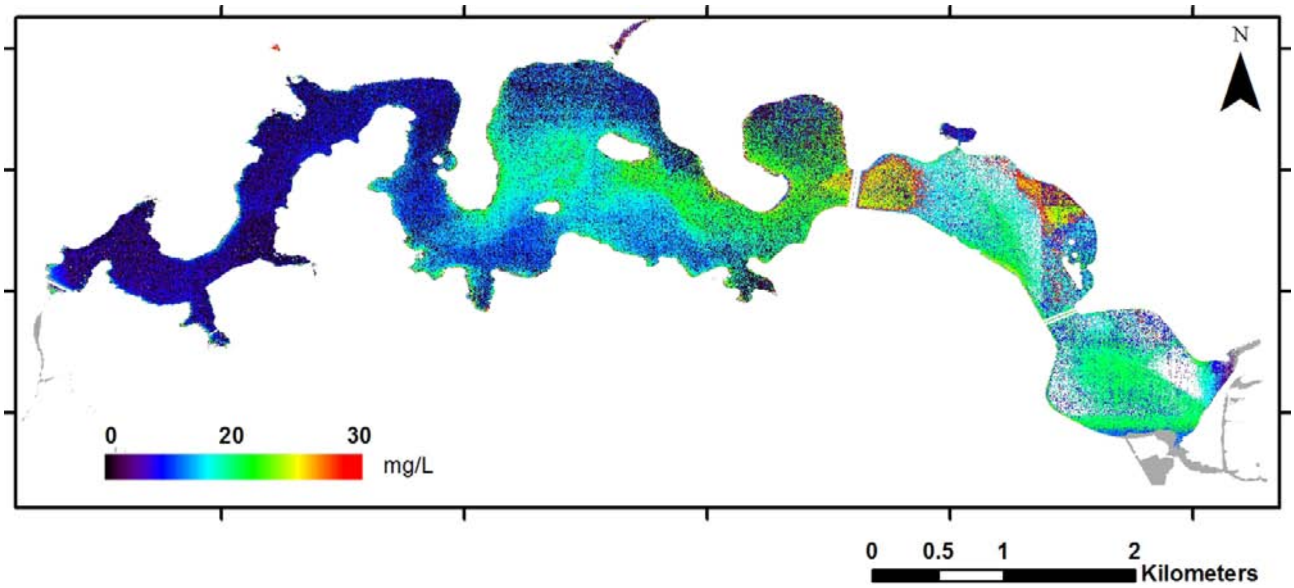


Figure 4-22 Non-algal particulate concentration in Lake Burley Griffin from a Worldview-2 image 17 March 2010

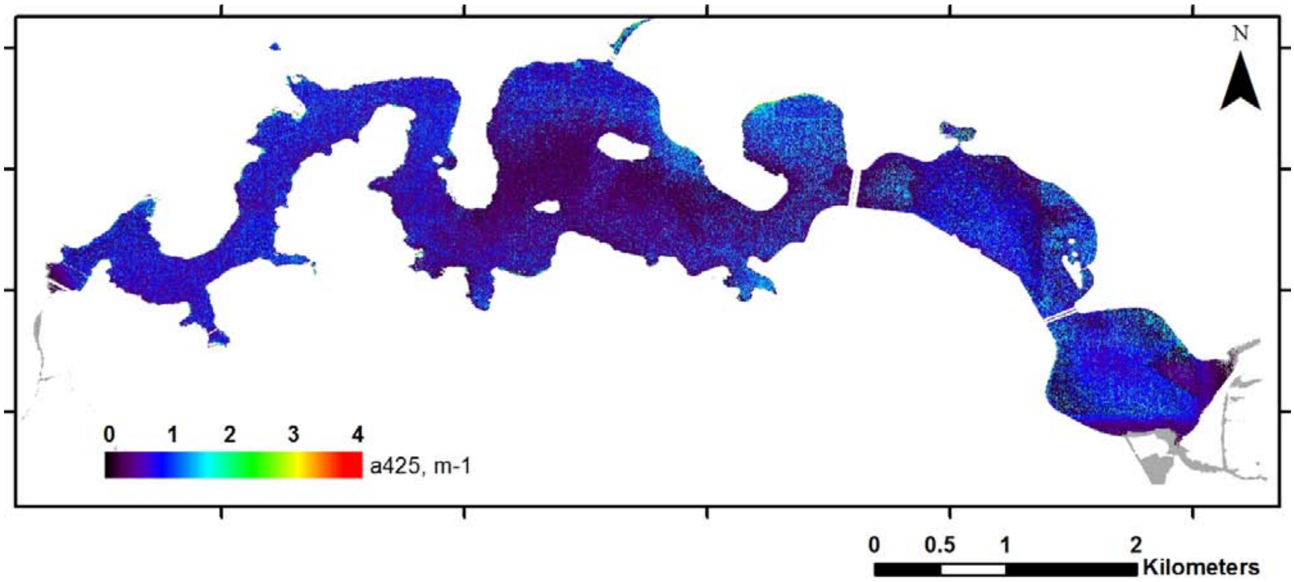


Figure 4-23 Coloured dissolved organic matter in Lake Burley Griffin from a Worldview-2 image 17 March 2010

Figure 4-24 shows the result of applying a semi-empirical blue-green algal pigment (cyano-phycocyanin) algorithm to the WorldView-2 image. Figure 4-25 shows the distribution of the water types (measured during two field campaigns in January and March 2010) according to the aLMI algorithm processing. The algorithm determines for each pixel in each image what the bio-optical properties are (from which specific *in situ* sample numbered 1 through to 10, see Legend). In the image, this distribution shows patterns which likely indicate the water masses dominantly present.

Thus the aLMI algorithm can also provide images of water types and how they are distributed due to biological, chemical and physical differences.

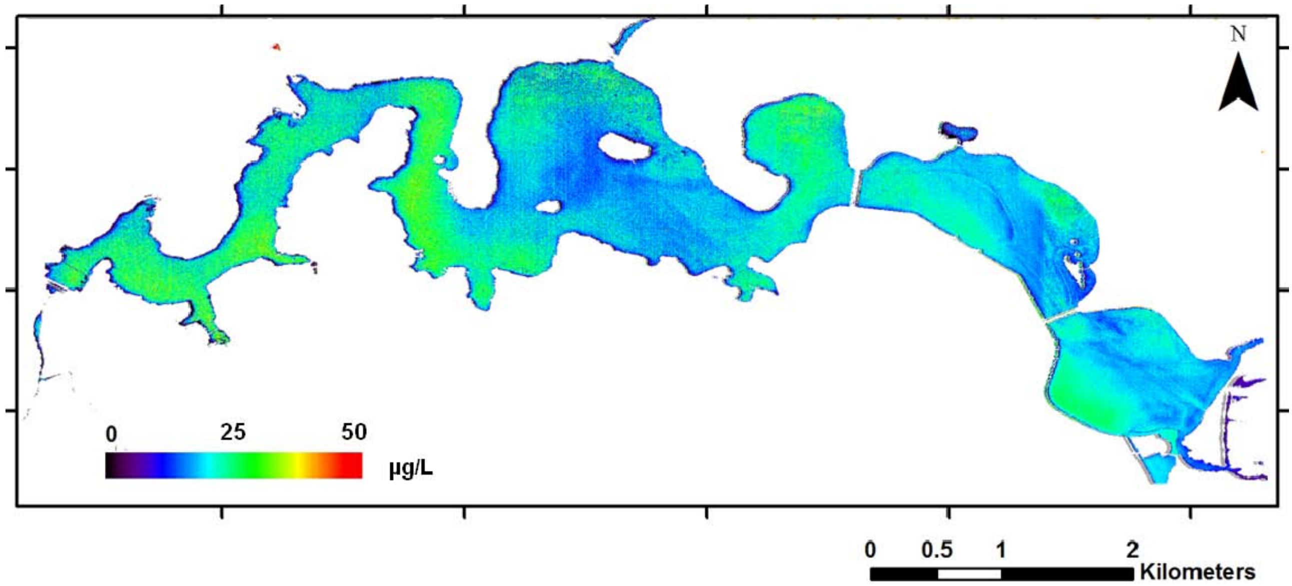


Figure 4-24 cyano-phycocyanin concentration in Lake Burley Griffin from a Worldview-2 image 17 March 2010

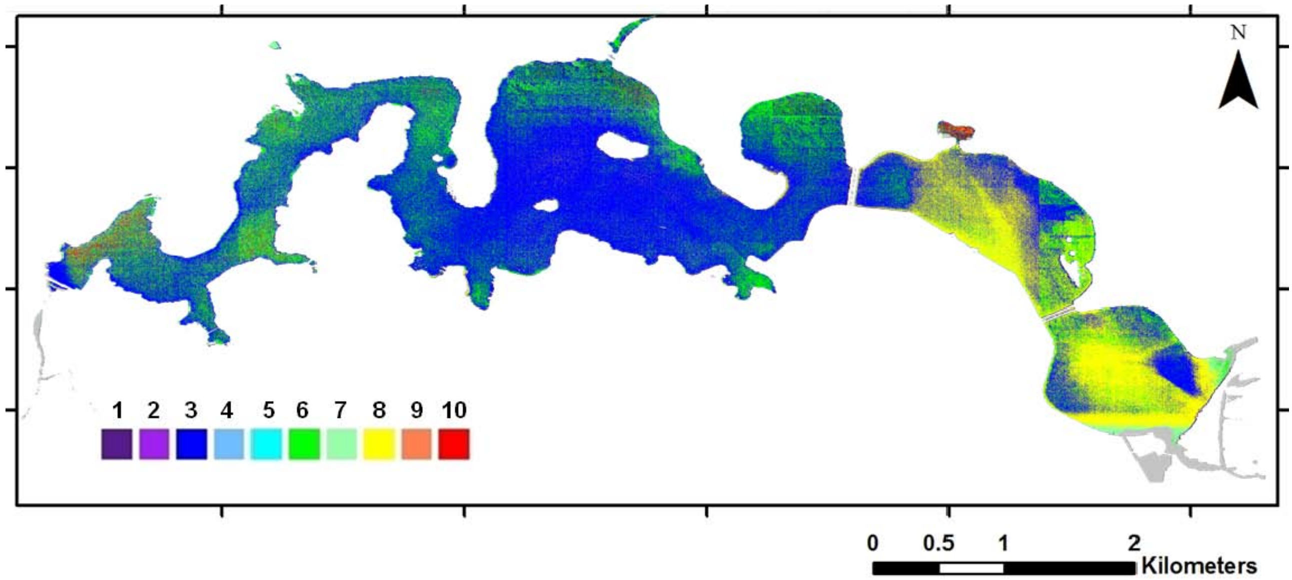


Figure 4-25 Water types (1-10) in Lake Burley Griffin from a Worldview-2 image 17 March 2010

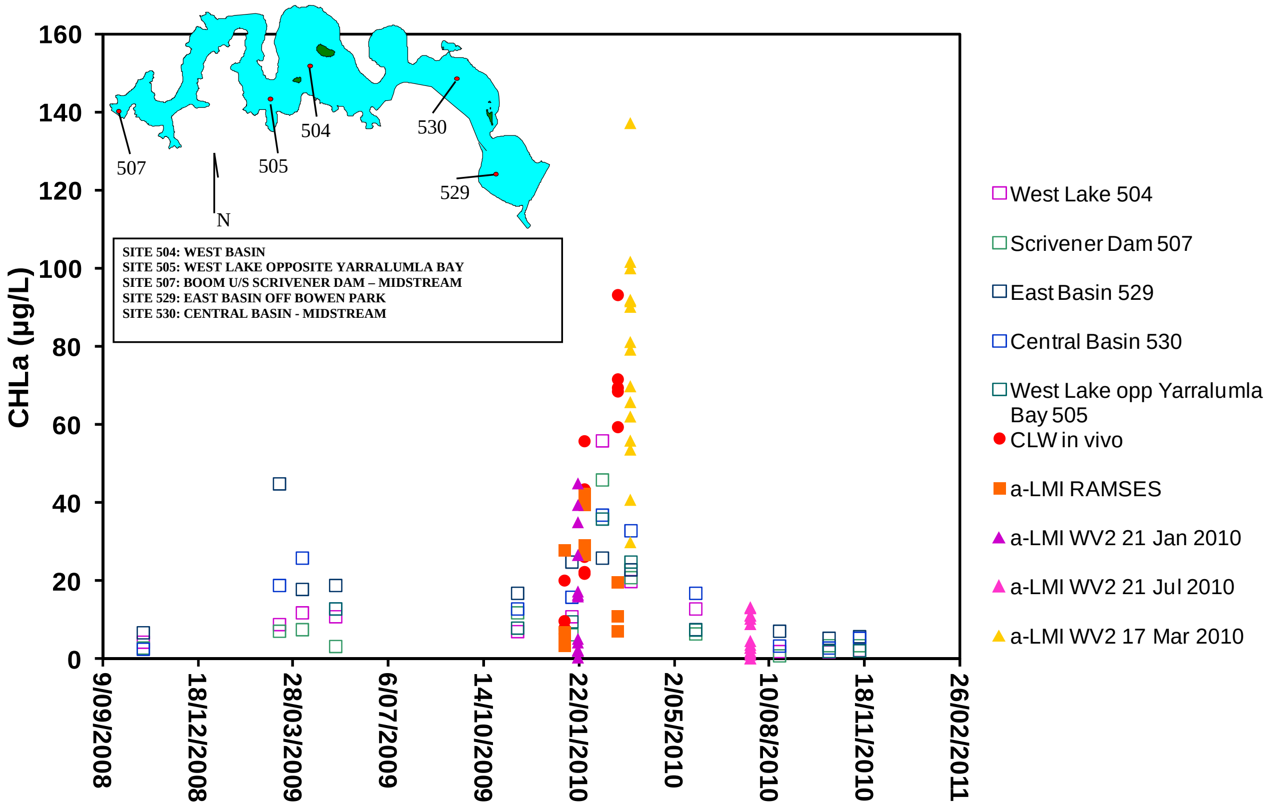


Figure 4-26 Comparison of chlorophyll concentration from *in situ* measurements, *in situ* spectra (RAMSES), WorldView-2 imagery (aLMI WV2) from 2009-2010

Figure 4-26 presents the chlorophyll results from the Worldview-2 data, and compares them with CHL concentration measured from *in situ* discrete measurements and *in situ* radiometry. Figure 4-27 presents the same comparison for NAP. Notably, few of the presented measurements (*in situ* or satellite data) coincided with each other.

CHL measured *in situ* by the National Capital Authority varied between 0 to 45 µg/L, whilst the CSIRO *in situ* measurements varied between 8 and 95 µg/L. Chlorophyll derived from spectral *in situ* measurements (measured using the RAMSES system - only on January 2011) varied between 1 and 40 µg/L, matching the same range of values as the National Capital Authority data. Chlorophyll concentrations estimated from the three WorldView-2 images (January-July 2010) varied between 0 and 105 µg/L and the Landsat data between 2 and 75 µg/L for lower Lake Burley Griffin near the Scrivener Dam. These ranges of values have a small departure from one another, and are in the approximate range of CSIRO's *in situ* data, though it is possible the algorithm may be overestimating chlorophyll concentration.

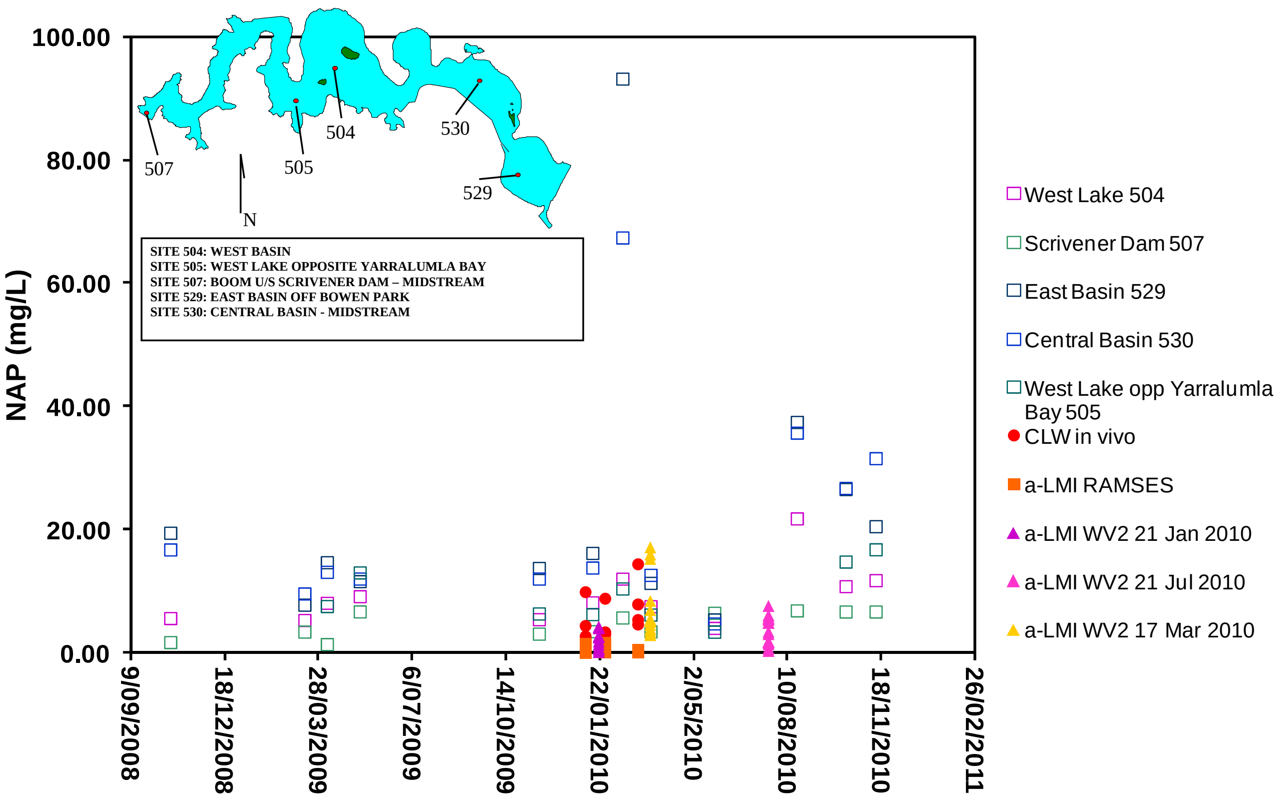


Figure 4-27 Comparison of non-algal particulate concentration from *in situ* measurements, *in situ* spectra (RAMSES), WorldView-2 imagery (aLMI WV2) from 2009-2010

Figure 4-27 shows that *in situ* NAP matter measured by the National Capital Authority varied between 2 to 37 mg/L, whilst the CSIRO measurements varied between 3 and 15 mg/L. The spectral *in situ* measurements (only on January 2011) ranged between 0 and 3 mg/L, showing little agreement with the National Capital Authority measurements, but matching the low range of the CSIRO measurements. The three WorldView-2 images (January-July 2010) varied between 0 and 17.5 mg/L, and the Landsat images varied around 7 mg/L for lower Lake Burley Griffin near the Scrivener Dam, falling within the range of the CSIRO *in situ* measurements. The results presented are indicative and need proper validation to be made more robust.

Figure 4-28 presents the CHL results from the NBAR-Landsat corrected spectra. The variability between *in situ* CHL sites in Lake Burley Griffin near the two dates of Landsat imagery was high. However, CHL derived from the NBAR corrected imagery seems to be underestimated, falling below the range of CHL estimated *in situ*.

There are several potential reasons for the mismatch between the *in situ* and the Landsat-derived CHL measurements. As with the Murrumbidgee case study, it is possible the NBAR correction is not appropriate for this application. Another possibility is that with the larger Landsat pixels, the CHL concentration values represent an integrated measurement over a large surface. *In situ* point samples represent just a few litres of water, whereas a Landsat pixel represents 900 m^2 of surface water. Phytoplankton abundance is spatially patchy and highly dynamic, controlled by wind and stratification processes (Sherman et al., 1998). It may be that spatially-integrated CHL estimates are lower because the mean concentration values were driven by the large amounts of low concentrations rather than the few, patchy high concentration areas. However, the Worldview-2 images at 2 m spatial resolution do not indicate patchiness, although the images do not occur on the same dates. Additional research is needed to resolve these issues of scale and statistical summarization of earth observation-derived results.

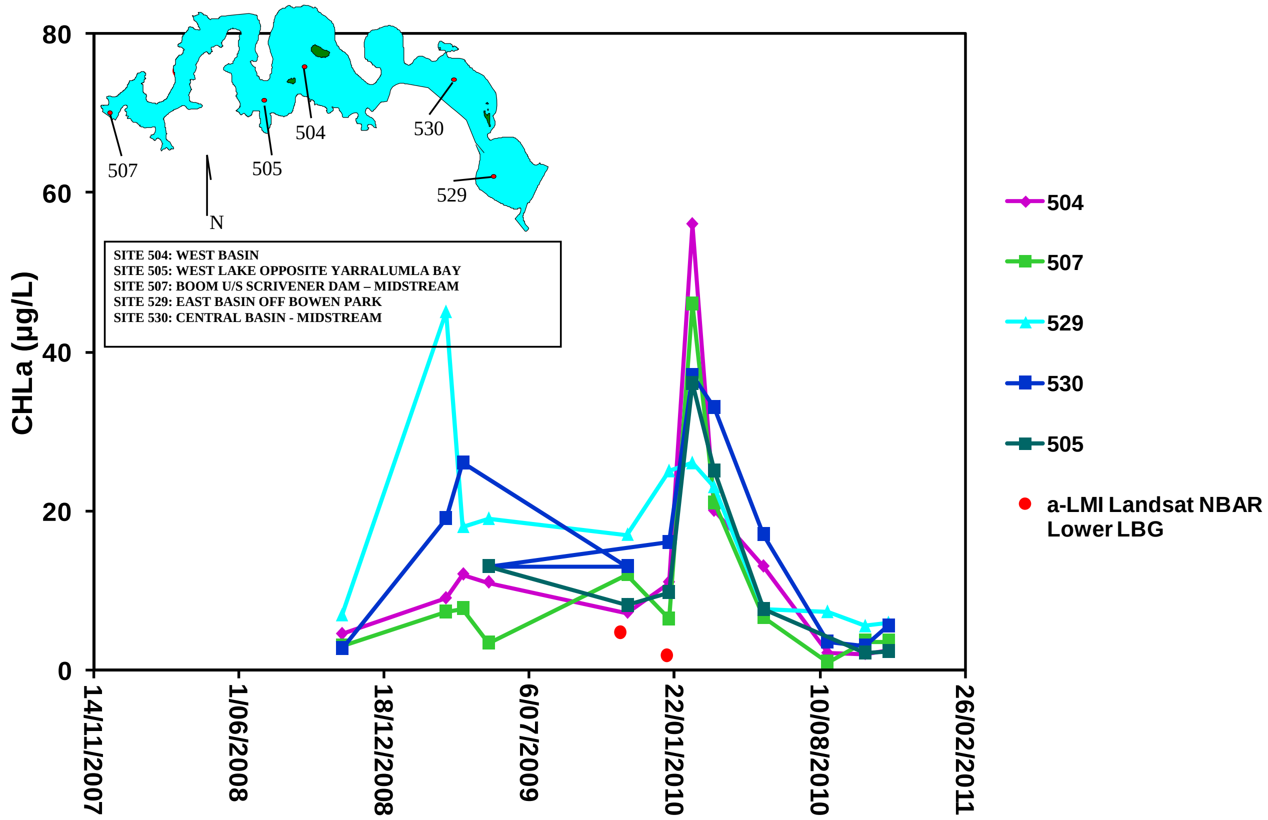


Figure 4-28 Comparison of chlorophyll concentration from *in situ* measurements and NBAR-corrected Landsat from 2009-2010

4.8 Case Studies Summary

The case studies tested whether earth observation of water quality is sufficiently far developed to be able to produce multiple examples of retrospectively processed satellite images varying in temporal frequency (once a day to once a month or so), spatial resolution (one meter to 0.3 km pixels), spectral resolution, radiometric resolution and in costs of unprocessed satellite data acquisition (ranging from 0 to 30 AUD per km^2).

The conclusions that can be drawn from these studies are limited, as it was difficult to validate the results due to a lack of concurrent *in situ* water quality data. However, relative accuracy appears to be acceptable. Results fall within the range of values reported in the literature or the range of values measured at different times for the same water body. Where accuracy appears to be questionable, it may be a result of

1. Poor parameterisation of the algorithm due to insufficient bio-optical data
2. Poor atmospheric correction. The NBAR correction was not designed for estimating water body reflectance, although initial inspection of the results do not fall outside the range of possible and expected values.
3. Potential over/under estimation by the algorithms
4. Mismatch between concentrations measured by *in situ* point samples and concentration integrated over the large surface area contained in a pixel

The water bodies covered varied from Queensland to NSW to Victoria to South Australia, from lakes to wetlands to rivers to reservoirs. Estimates or examples were presented during drought, normal and flood conditions. In some cases an atmospheric and view and sun angle correction method was applied in operational mode by GA after which CSIRO applied their operational aLMI algorithm. From these cases sensible results were obtained for water quality assessments by Landsat data. However, in all case studies, further data was required, yet unavailable, to conduct rigorous validation that would be necessary to meet the requirements of end users for an operationalised earth observation monitoring program. Additional *in situ* data is needed to create the sufficient validation and error reporting needed for end-user confidence.

4.8.1 MERIS RESULTS SUMMARY

MERIS data were successfully used to derive chlorophyll, NAP, and CDOM in the Burdekin River system from October 2008 and May 2009 with sufficient accuracy and precision (Campbell et al., 2011b). The semi-analytical matrix inversion method, a physics based approach to deriving water quality information from remotely sensed data, was extended to the flooding events in this system; CHL, NAP, and CDOM were mapped in 4 MERIS images from December 2010 and January 2011. MERIS data were also used to derive CHL concentrations in flood conditions in the lower Murray region that match previously published measurements. For this purpose an operational satellite data processing package freely available from The European Space Agency was used.

These freely available satellite data could be processed to water quality to provide a systematic assessment of trends and anomalies in many different river systems. It would require development or assessment of best atmospheric correction method, bio-optical parameterisation of the aLMI algorithm and a thorough analysis of available *in situ* data sets- including converting these datasets to earth observation type water quality variables (e.g. translating turbidity measured in NTU to TSM).

4.8.2 LANDSAT RESULTS SUMMARY

Landsat has the spatial and temporal resolution necessary to image extreme events such as the black water flood event surrounding Kerang in January 2011. CHL, CDOM and NAP were all estimated for several Murrumbidgee water bodies from the Landsat imagery. The implementation of the aLMI algorithm for CHL and NAP retrieval on Lake Burley Griffin resulted in mapped values that closely matched *in situ* measurements conducted by CSIRO. However, the aLMI could not be implemented on Landsat data collected over Lake Eyre. This failure is likely due to lack of *in situ* data for proper parameterisation of the inversion algorithm.

4.8.3 WORLDVIEW-2 RESULTS SUMMARY

Worldview-2 data has the unique capability to provide medium spectral resolution data with high spatial resolution on a commercial satellite platform. Its capability of being pointed provides “on demand” temporal resolution with some limitations. Due to its high spatial resolution and moderate spectral resolution, it can image smaller water bodies of interest, and may be most appropriate for targeted regional or event applications. In the case of Lake Burley Griffin CSIRO correction algorithms and aLMI successfully mapped CHL, NAP, and CDOM, retrieving values that fell near the range of values measured *in situ* by CSIRO.

Part III A National Operational Inland Water Quality Monitoring System

5 Scoping an earth observation based national operational system for inland water quality monitoring

The end-user requirements (policy, legislative, environmental and climate change drivers) should determine the development of a national operational system for inland water quality monitoring. However, the ideal satellite sensor system for inland water quality does not exist; there are tradeoffs between spatial, temporal, spectral and radiometric resolution. Thus, the available satellite sensors for retrospective, current and future inland water quality detection and monitoring are one of the boundary conditions in developing a national inland water quality monitoring system using earth observation.

As illustrated in the case studies in chapter 4 there is a trade-off for inland water quality assessment between the temporal frequency (once a day to once a year), the spatial resolution (2 m to 1.2 km pixels), spectral resolution (and the related issue of more water quality variables at higher confidence level), radiometric resolution (how accurate and how many levels of reflectance are measureable) and costs of unprocessed satellite data acquisition (ranging from 0 to 30 AUD per km^2).

Therefore, this chapter has four components relevant to scoping an earth observation based national operational system for inland water quality monitoring:

1. Describe a national operational system for inland water quality monitoring
2. What water quality variables could be part of an operational earth observation based inland water quality monitoring implementation?
3. What satellite sensor systems are potentially available for retrospective, current and future assessments of inland water quality?
4. What investments are required to operationalise earth observation of inland water quality? Addressing issues of building the capacity and the analysis and reporting requirements.

5.1 A national operational system for inland water quality monitoring

Many policy, legislative, climate change and environmental drivers exist for developing a national operational system for inland water quality monitoring as described in chapter 2.1. They vary from condition and trend assessments for SoE reporting and NWQAs to annual state or water basin-based assessments, to seasonal, monthly, fortnightly assessments required by regional and local water quality management.

There are two systematic approaches possible to developing a national operational system for inland water quality monitoring: a bottom-up approach (local-regional-water basin-state-commonwealth level), or a top-down approach from commonwealth to local scale.

A hierarchical, top-down approach is better suited to Australia's policy and program needs, as water quality relevant information from a national system will be informative to regional scale assessments. Using local scale assessments as the initial driver may lead to differing priorities, methods and approaches that would be difficult to synthesize at a higher aggregation level. Whereas using national scale assessments as the initial driver provides systematic and consistent information that provides benefits at multiple scales. Using the national drivers of SoE and NWQA reporting as prime drivers for developing a national operational system provides the most strategic approach to systematic water quality monitoring. Such an approach would be beneficial to state, basin, regional and local level management levels in several ways:

- If earth observation based inland water quality assessment were operational for NWQA reporting it would automatically also be available for SoE reporting as well as state or river basin, regional and local

water management levels. There is a clear avenue for infrastructure investments at state, basin, regional and local level that will support this development in smart and effective implementations.
- A national long term approach will encourage state, basin, regional and local level organizations to invest as they would experience a large return for investments. *In situ* measurement methodologies (either by field sampling or *in situ* autonomous instrumentation) can be coordinated to support quantitative earth observation information at all scales.

5.2 Water quality information products for the national system

The water quality variables directly measureable in the water body surface layer (down to the visibility of depth) suitable for a national operational system for inland water quality monitoring from earth observation are given in Table 5-1.

Table 5-1 Water quality variables for a national operational inland water quality monitoring system from earth observation

WATER QUALITY INFORMATION	WATER QUALITY VARIABLE
Primary production and eutrophication status	CHL
	CPC
	CPE
	Surface algal blooms
Aquatic carbon content, carbon fluxes	CDOM
Erosion, re-suspension and deposition	TSM (ΣCHL+NAP)
Light climate information related to the combined effects of algae, CDOM and suspended matter	K_d
	Transparency
	Turbidity
Ecological condition	Emergent macrophytes
	Submerged macrophytes

CHL=chlorophyll; CPC=cyano-phycocyanin; CPE=cyano-phycoerythrin, CDOM=coloured dissolved organic matter; TSM-total suspended matter; NAP=non-algal particulate matter; K_d=vertical attenuation of light

By assimilating earth observation derived water quality information with 3-D hydrodynamic and biogeochemical models, depth resolved assessments in hindcast and nowcast form can be made as well as predictions of these integrated assessments. The methodology to this data-assimilation is in development and will provide improved understanding and management relevant prediction tools.

Water surface temperature information can be added to this suite of information from earth observing sensors to improve understanding of thermal cooling (deep water reservoir outlets) or thermal heating.

In the next section the satellite sensors available for retrospective, current and future inland water quality detection and monitoring are discussed in the context of boundary conditions in developing a national inland water quality monitoring system using earth observation. They are discussed in a sequence that aligns with the proposed hierarchical framework of SoE and NWQAs: from state or river basin to regional and local water management reporting levels.

From the national to local scale the sensors most suitable would be the low spatial, high temporal resolution earth observation sensors (most suitable for national level reporting), via medium spatial and temporal resolution (suitable for national to river basin and state and regional level reporting) to high spatial resolution sensors suitable for detailed level reporting.

5.3 Available satellite sensor data relevant for inland water quality monitoring

For earth observation based inland water quality monitoring, there are three categories of input satellite data with associated assessment of requirements to operationalise:

1. The freely available low spatial resolution, high temporal resolution, high spectral and high radiometric resolution satellite imagery systems such as SeaWiFS, MODIS, MERIS, OCM-2 and VIIRS currently, and Sentinel-3 in the near future.
2. The free to inexpensive medium spatial temporal and radiometric resolution, low spectral resolution imagery systems such as Landsat, the IRS series currently, and Landsat Data Continuity Mission and Sentinel-2 in the future.
3. The commercial high spatial resolution, high temporal (expensive) to medium temporal (affordable) to low temporal (most affordable) resolution, low to mid spectral and radiometric resolution imagery systems such as QuickBird, IKONOS, RapidEye, GeoEye, WorldView-2, etc with many follow-up systems such as the SPOT-6 and 7 (incorporating blue spectral bands) and WorldView-3 planned.

5.3.1 FREE LOW SPATIAL RESOLUTION, HIGH TEMPORAL RESOLUTION, SATELLITE IMAGERY SYSTEMS

In Australia the MODIS processing for land, coastal and continental shelf and oceanic waters is already automated through IMOS, TERN, WIRADA and other infrastructure investments. The most relevant development for inland and near-coastal waters is the eReefs Project that will operationalise MODIS satellite image processing for water quality in the complex waters of the Great Barrier Reef lagoon in close collaboration between CSIRO and Bureau. Thus the least investment in resources for operationalisation of earth observation for inland water bodies will be required for MODIS data. The drawback is that MODIS (2002-present) and VIIRS (late 2011 onwards) data have low spatial resolution, and their spectral band positioning is sub-optimal for inland and near-coastal water quality.

The most suitable satellite sensor system with sufficient temporal frequency for inland and near-coastal water quality (such as estuaries) are the MERIS and, after launch in 2014, the SENTINEL-3 OLCI sensor systems; they have the best compromise between temporal resolution (one overpass every two to three days) and spatial resolution (300 m pixels) and they have spectral bands dedicated to complex waters (MERIS=15, OLCI=22). Coupled with high radiometric resolution, these will likely be the most sensitive sensors to be available or launched in the next 10 years. The Sentinel-3 system will consist of two sensor platforms thereby increasing temporal coverage to once every 1 to 2 days. The ESA has committed to guaranteeing data continuity until 2025, by implication this means any investments in operationalising this data for Australia will have long term benefits.

The drawback for inland water quality assessment is that a suitable size of a water body for use with this sensor is at a minimum more than 300 x 300 m (as for each overpass the exact location of the pixels shifts slightly). However, to obtain one reliable pixel of a water body for each overpass a water body size of 3 to 4 times the pixel size thus 1,200 x 1,200 m is effectively the requirement to ensure one “pure” pixel that does not contain signals from surrounding land and vegetation (see 3.6.1. and Table 3-3).

The use of such satellite sensors deserves additional research especially for application to extreme events. In instances where large areas are covered by water such as river floods, *in situ* measurements are much sparser. Therefore, even a relatively small amount of valid river (and floodplain) pixels may be very worthwhile in understanding river and floodplain water quality processes. Further, retrospective processing of the satellite archives of MODIS (1999 onwards) and MERIS (2003 onwards) for inland water quality would underpin trend and anomaly detection and knowledge around Australia for the larger water bodies.

5.3.2 AFFORDABLE MEDIUM SPATIAL, TEMPORAL, AND RADIOMETRIC LOW SPECTRAL RESOLUTION IMAGERY SYSTEMS

These satellite sensors have a spatial resolution enabling systematic estimation of water quality of water bodies at about 3 to 4 times their actual pixel size resulting in minimal water body sizes of about 120 by 120 m for Landsat (see 3.6.1. and Table 3-3). The lower spectral resolution indicates less accurate discrimination of optical water quality variables, inability to detect CHL under high turbidity conditions and inability to detect CPC and CPE. The imminence of the Landsat Data Continuity Mission (with 30 m pixels and an extra blue spectral band) and the Sentinel-2 mission (with two satellites planned with improved sensors at 10 m, 20 m and 60 m pixels) indicates that, merged with the existing Landsat data archive going back to 1984, there is a wealth of potential water quality information in the past, the present and the future. These sensors will image all of Australia systematically with each overpass and this data will be archived and made easily available to the research community. This is especially important when compared to the next category of high spatial resolution sensors that will only acquire data when programmed to do so (usually on the basis of a client order).

5.3.3 THE COMMERCIAL HIGH SPATIAL RESOLUTION IMAGERY SYSTEMS

These satellite sensors have a spatial resolution enabling systematic estimation of water quality of small water bodies of interest. WorldView-2 can provide data for water bodies of 7 x 7 m and greater, RapidEye about 20 x 20 m. The lower spectral resolution (as compared to MODIS and MERIS) indicates less accurate discrimination of optical water quality variables and, inability to detect CHL under high turbidity conditions and inability to detect CPC and CPE. The exception is WorldView-2, which has sufficient spectral resolution to detect cyanobacterial pigments. Most of these sensors collect data “on demand”, meaning temporal resolution is variable, as is cost. As these sensors mainly acquire data for commercial purposes, there is a more disparate archive that focuses on areas where the commercial providers have interests or expect a market demand. This may rule out default remote area coverage.

5.3.4 PROPOSED SATELLITE SENSOR SYSTEMS

Data from three satellite sensor systems are currently most suitable for operationalisation: MODIS, MERIS and LANDSAT. The reasons are:

- Data archives exist and are complete.
- Data format is accurately known. Much published research is available on these sensors and their specifications, including how to correct for sensor degradation over time.
- Many agencies and programs such as NASA, USGS, ESA, GA, IMOS and TERN have spent and will spend considerable resources making unprocessed data systematically available at a quality level.
- Much is known about atmospheric correction, sun glint removal and automated flagging of pixels of poor quality for these sensors. Systematic and reliable atmospheric correction over inland water targets is within reach but has not yet been accomplished.
- Each of these sensor systems have follow-up sensor systems planned through to at least 2020 that will include improvements to existing technologies (although the VIIRS and JPSS systems from the US will have fewer spectral bands than MODIS).

For an operational system a significant effort must be spent *a priori* on identifying the long term information requirements by the end-users. For example, the requirement to report once every 5 years for the SoE has very different implications than the requirements of a regional water manager that needs to be alerted on a daily basis to blue-green algal blooms or an emergency management application related to flooding.

Commercial high spatial resolution satellite earth observation applications certainly exist for specified intensely used water bodies such as water reservoirs, rivers near intakes for irrigation or drinking water, and for urban lakes such as Lake Burley Griffin. Integrated use of commercial high spatial resolution satellite imagery for water quality, wetland and riparian vegetation mapping, land use and vegetation mapping is more cost-effective than single purpose water quality mapping.

5.4 Operational satellite data processing: building the capacity

To systematically process satellite data to water quality information products there are five general steps (see Figure 5-1):

1. Satellite data stream: access to raw satellite data, either via direct broadcast to a satellite direct broadcast receiver in Australia, or via ftp or via a physical data carrier.
2. Pre-processing:
   - Conversion of raw top of atmosphere volts to top of atmosphere radiance data.
   - Correction of the top of atmosphere radiance data for view angle, sun angle and atmospheric effects to produce an above-water normalised water leaving radiance or remote sensing reflectance product. This step may also involve water surface sky and sun glint removal.
   - Geometric correction, with as little loss of original spatial resolution and signal as possible.
3. Water body identification to ensure processing of pure water pixels only and to assess water body distribution (see 2.5 on WIRADA outcomes).
4. Water quality information retrieval from the pre-processed satellite imagery by application of a robust algorithm such as the aLMI approach. Physics-based water quality inversion algorithms require proper parameterisation with the aquatic ecosystem-relevant concentration-specific inherent optical properties.
5. Water quality information product: analysis and reporting tailored to the end user requirements.

Figure 5-1 provides a schematic of the processing for physics-based processing of earth observation data for inland water quality products using the aLMI method as an example.

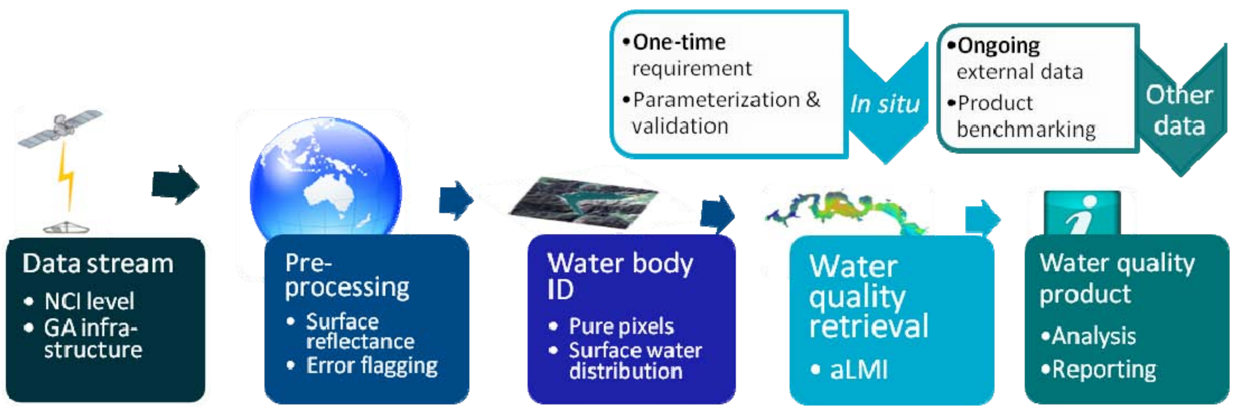


Figure 5-1 Schematic of processing for inland water quality products from earth observation data

5.4.1 COST-BENEFIT CONSIDERATIONS

The costs to the provider of water quality information from the earth observation are a combination of costs associated with:

- The acquisition of unprocessed satellite data
- Pre-processing and processing of the satellite data
- Archiving and distributing the information products

The value of earth observation derived information to the end user can differ from application to application. This can vary from the case where earth observation data is the only form of information to the case where earth observation-based information is an auxiliary and integrative measurement from *in situ* data and modelling estimates are available on a regular basis.

One cost aspect not assessed for a potential end-user is to is whether earth observation derived-data augments their existing data sources (no cost saving but improved management relevant information) or whether the earth observation derived data information can replace existing sampling and measurements (significant cost saving).

A more complex situation also not assessed is where no information currently exists but can now be retrieved from the satellite archives; the value of that information is more difficult to quantify. The organization(s) that use the data will need to make infrastructural adjustments to be able to ingest the data and transform it into their management-relevant practice.

Figure 5-2 through Figure 5-5 contain the information used to assess the investments required to operationalise earth observation for inland water quality monitoring. In this discussion operationalising Landsat is considered to be the first data stream (it is also possible to consider MODIS or MERIS data as the first data stream to be operationalised). Subsequent operationalisation of earth observation data streams will require less investments as some investments are only needed once.

Specifically, the investment of resources to carry out the first expert bio-optical parameterisation is a one-off investment; the resulting parameterisation information can be easily adapted to any other sensor suitable for inland water quality monitoring. Therefore we first describe the costs and investments required for operationalising Landsat data.

Figure 5-1 and Figure 5-3 illustrate the investments and process required to operationalise water quality information delivery from earth observation for the first time. Figure 5-2 shows a flowchart describing the sequence of processing, initial expert bio-optical *in situ* measurements required for parameterisation of the aLMI and the role of *in situ* data from the water quality management authorities for validation. This flow chart refers to the mid-section of Figure 5-3. In Figure 5-3 the mid-section in italics is work that only needs to be performed once as the parameterisation data is valid for all other satellite sensors.

Required investments for the first operationalisation process

The first operationalisation process will require investments in expert bio-optical data parameterisation, and testing and refining the aLMI. The costs for this activity are approximately 1.4 FTE and 200-280k AUD operational costs. The operational costs are coarse estimates only, subject to the amount of support and coordination between water management authorities, the number of water bodies to be sampled, access to existing instrumentation, etc. These costs are one-off, and the resulting parameterisation can be applied to other current and planned optical sensors (Table 3-1).

The costs estimates are detailed below. Table 5-2 summarises the costs associate with expert bio-optical forward and inverse model parameterisation measurements. In order to establish a basis for sampling strategy and to identify potential virtual stations, an assessment of the variability of water quality and the sources of variability is required. For this, 0.2 FTE is needed. Expert bio-optical measurement field costs are estimated to be 160k AUD using 0.8 FTE staff time based on:

1. Approximately 30 representative water bodies need to be sampled for a large catchment or basin
2. Leasing/borrowing existing bio-optical instruments

Laboratory analyses for algal pigments by HPLC, spectrophotometric analysis of light absorption by algal pigments, NAP and CDOM and gravimetric TSM will be 40k AUD. If triplicate sample measurements per site are required to establish a measure of accuracy for the *in situ* measurements then these costs triple to 120k AUD.

Once all *in situ* expert bio-optical measurements are made, 0.4 FTE is required to quality control and quality assessment the measurements, and parameterise the aLMI algorithm. These 0.4 FTE will also be used to process one year of earth observation, refine the parameterisation (with possible requirements for additional bio-optical measurements), and then process the entire satellite archive.

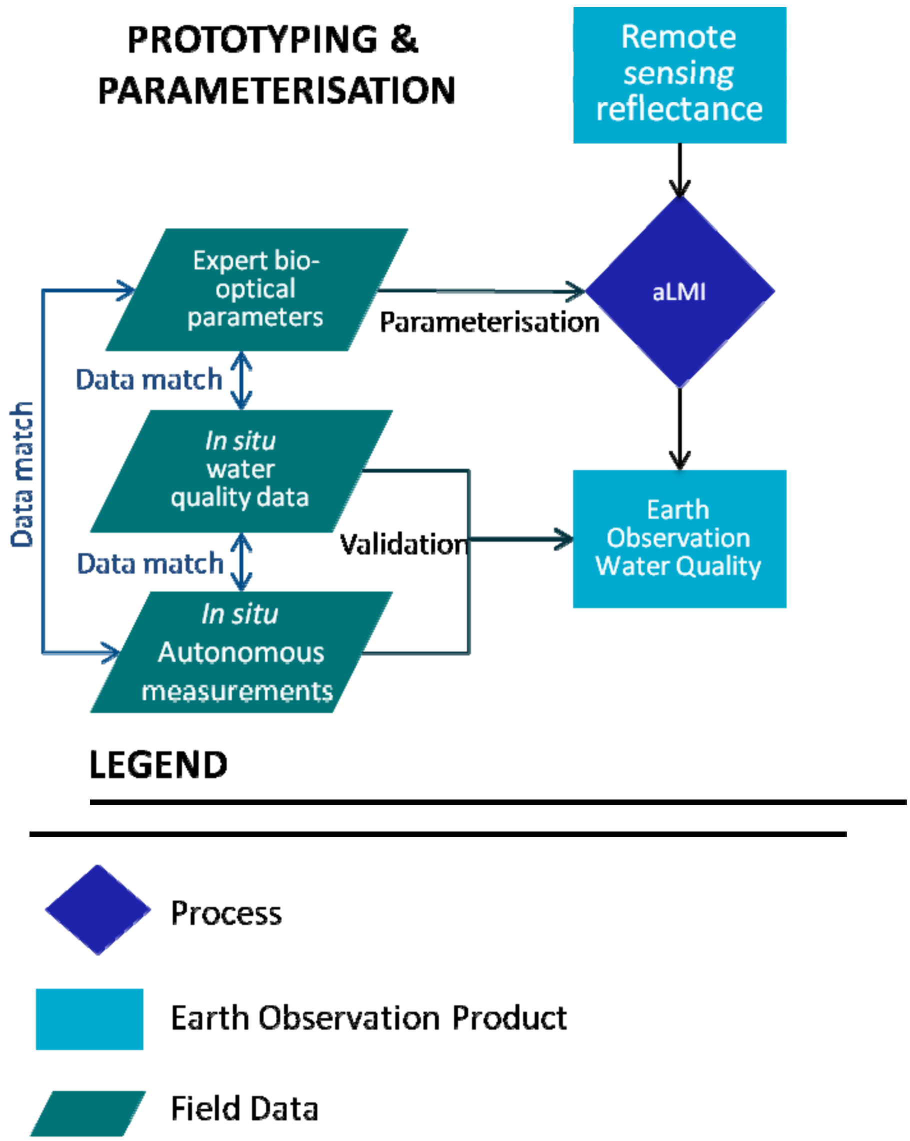


Figure 5-2 The sequence of data processing for initial prototyping and parameterising for an earth observation derived water quality product

Figure 5-3 Analysis of the first investment chain from satellite data reception to water quality product reporting

Table 5-2 Costs associated with expert bio-optical measurements

	WATER QUALITY VARIABLES							
	HPLC	SPECTRO-PHOTO	CELL ID & COUNT	LISST-100 [a]	BB9 [a]	AC-S [a]	SD	SPECTRO-RADIO
	LAB-BASED SAMPLE ANALYSIS			*IN SITU* SUBMERGED SUPERVISED				ABOVE/IN WATER
Sensor cost range (1000s AUD)				50	30	50	0.05	30-70
Sample cost range (AUD)	90-180	130-260	WMA					

WMA = water management authorities: costs are variable and often already have been invested by WMAs and thus are not an additional cost associated with operationalising earth observation methods.

[a] Instruments that are currently deployed at the Lucinda Jetty within IMOS context. Other instruments are available from other manufacturers. LISST-100 is a submersible laser scattering instrument that measures concentration and particle size spectra, pressure and temperature. BB9 is a backscatterometer at 9 wavelengths. AC-S is a hyperspectral light absorption and beam attenuation meter.

Required investments for operationalising Landsat

GA has invested significantly in systematic NBAR processing of the entire Australian Landsat archive. Currently the archive of processed data exists from 2000 to present. The approximate investment for this was about 6 FTE plus operational costs.

For inland water quality measurement from earth observation, several one-off activities are required:

- In order to evaluate and, if needed, adjust the NBAR atmospheric correction to be accurate enough over water targets about 0.3 FTE investment in expert atmospheric correction staff is needed.
- Systematic water body identification and assessment of pure water pixels needs about 1 (possibly 2 FTE) to operationalise-although a prototype is already available through WIRADA.
- The cost for data storage at NCI is already met through existing GA activities. The additional processing costs are in the order of a few thousand dollars.

For a systematic information supply chain and for reporting, investments will need to be made at the operational institute level. A very approximate estimate is that this would involve about 2 to 4 FTE based on appointing new staff for this purpose.

Required investments for operationalising MODIS or MERIS

Figure 5-5 Analysis of the first investment chain from satellite data reception to water quality product reporting is shown in Figure 5-3. This figure illustrates the investments and process required to operationalise a water quality information delivery from earth observation data for an additional satellite sensor.

Presuming the one-off costs for expert bio-optical parameterisation have already been met for Landsat operationalisation the following costs are anticipated for operationalising MODIS 250 m or MERIS 300 m data. MERIS is used as an example in this costing scenario.

Operationalising the data stream for MERIS at NCI would take approximately 1 FTE. Pre-processing will require approximately 0.3 FTE. Pre-processing includes validating and, if needed, modifying existing atmospheric correction methods available from the BEAM-VISAT software of the European Space Agency.

Water body identification and pure pixel extraction require an investment of about 1 to 2 FTE, although reductions are possible if this has already achieved for Landsat data.

Approximately 0.2 FTE is needed to adapt and quality control the aLMI parameterisation using the same expert bio-optical data as acquired for Landsat operationalisation.

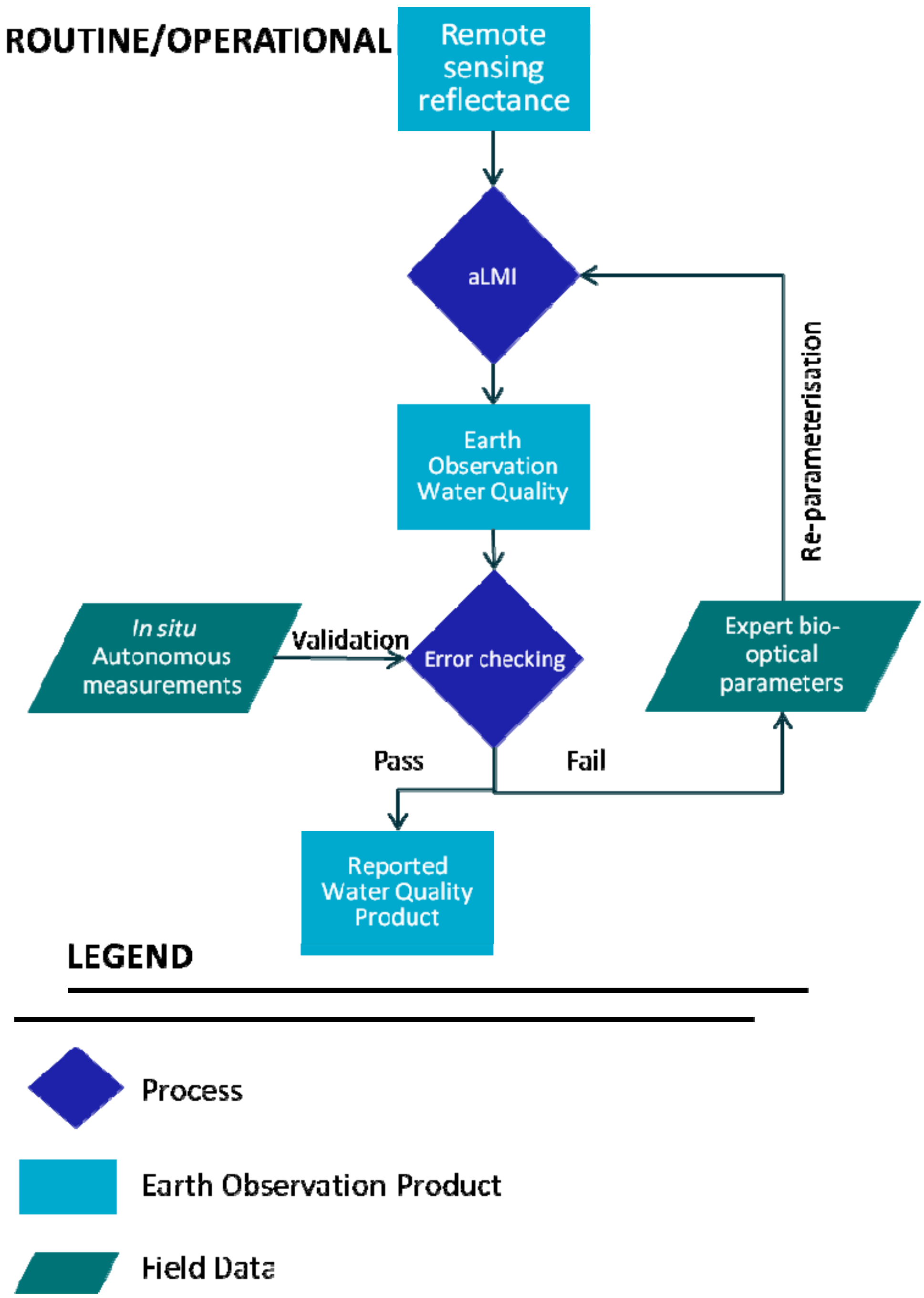


Figure 5-4 The sequence of data processing for operational earth observation derived water quality products

As with the Landsat scenario, for a systematic water quality from earth observation supply chain investments will need to be made at the institute level. A very approximate estimate is that this would involve about 2 to 4 FTE, based on appointing new staff for this purpose. If this has already been achieved for Landsat, the additional costs for performing this activity for MODIS or MERIS may be reduced 0.3-0.5 FTE.

Table 5-3 summarises the costs range of *in situ* discrete samples and *in situ* autonomous sensors recommended for deployment by water management authorities.

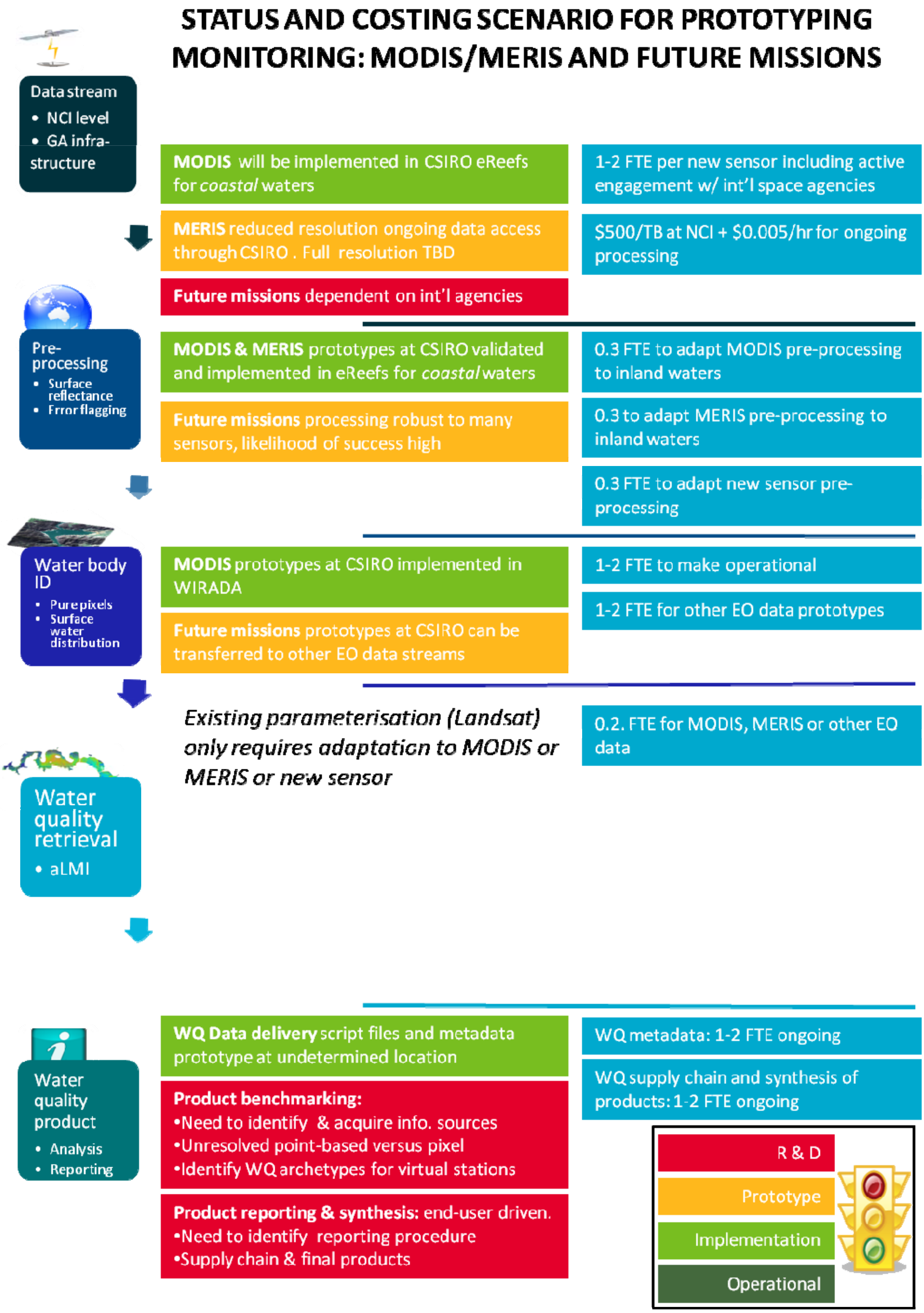


Figure 5-5 Analysis of the first investment chain from satellite data reception to water quality product reporting

Table 5-3 Cost range of *in situ* measurements and sensors

	WATER QUALITY VARIABLES						
	SPM + GRAVI-METRIC	FLUORO METERS	CELL ID & COUNT	K_d/ PAR	SINGLE λ LASER NTU	MULTI-λ LASER NTU	SPECTRO-RADIO
	LAB-BASED SAMPLE ANALYSIS			*IN SITU* SUBMERGED SUPERVISED			ABOVE/IN WATER
Sensor cost range (1000s AUD)	WMA	WMA	20-40	10-40	15	30	30-70

WMA = water management authorities: costs are variable and often already have been invested by WMAs and thus are not an additional cost associated with operationalising earth observation methods.

5.5 Operational satellite data processing: analysis and reporting requirements

Analysis and reporting requirements for water quality assessments from earth observation are linked to the actual application. This will vary from SoE reporting to daily algal bloom alerts for Lake Burley Griffin.

Because of insufficient end-user interaction with respect to earth observation applications at this stage, this area would need significant attention. End-user requirements should drive the analysis and reporting requirements. End-users will need training to become acquainted with earth observation-derived water quality information and the information need to be aware of the end-user requirements.

For an operational earth observation water quality information system, three different forms of analysis and reporting are anticipated. For each form, a focused iterative process between information providers and end-users will improve products and align expectations and delivery of relevant information products.

1. Status, trends and anomalies. Minimally, this would require hindcast and nowcast water quality information and the ability to interpret detected trends. These requirements align most with the top down approach to a national water quality monitoring system driven by SoE and NWQAs, continuing to state or river basin, regional and local water management level reporting levels.

2. Compliance monitoring. This requires reconciliation of earth observation derived water quality information with established water quality guidelines (i.e. ANZECC 2000). For example how are turbidity threshold values triggered when there are a hundred or a thousand satellite images with information? How would an exceedance be established in percentage terms spatially and temporally?

3. Near real time alerts for public health, such as potentially harmful algal blooms. Analysis would require an infrastructure for automated systems that perform preliminary processing of each received satellite image to detect a threshold level that may indicate an algal bloom. Reporting would be conducted via web and mobile phone (e.g. SMS or apps). This application would require much less focus on calibration, validation and error assessment as the warning information is relevant, not absolute levels of concentration of cyanobacteria.

In order to understand the detailed requirements of these different anticipated analysis and reporting schemes, case studies should be developed as demonstrations to initiate discussions between earth observation-derived information providers and end users. It is, however, possible to take SoE and NWQA reporting as an example and scope for analysis and reporting requirements. SoE and NWQA assessments must receive water quality information in the context of changes in land-use, water use, climate change and the effects of past management (or lack of management) in order to provide relevant information for adaptive management of the water resources.

Thus, retrospective and current reporting is equally important. Indeed, current reporting requirements are based on the context of retrospective state, condition and trend analysis. Under such requirements analysis of existing archives of satellite data becomes paramount. The analysis of water quality information products from earth observation will focus on validity, precision and repeatability. The consequence is that focus would be on calibration and validation of the water quality information products from different earth observation sensors, across different seasons, and encompassing all suitably sized water bodies in Australia.

The estimated time series of archival satellite data nominally contains:

- 600 Landsat images from 1984-2011
- 1000 MERIS images from 2003-2011.

The time series require screening for unfavourable image conditions such as cloud and smoke, followed by analyses of trends and anomalies both spatially and temporally. Such analysis requires highly systematically organised data structures of satellite images that can be examined from each of the space time and water quality information product dimensions.

Anomalies occurring during these periods could be identified and extracted for more detailed analysis. Anticipated examples of these analyses are:

- Assessing the wetting and drying cycles in the Lake Eyre basin water bodies and the effects on water quality.
- Analysis of Murray-Darling Water bodies since 1984, assessing the effect of different water management strategies, or black water events on water body condition.
- Seasonal cycle and increase or decrease of turbidity or eutrophication by frequency and severity of algal bloom assessment.

This information would equally be useful for the bi-annual NWQA assessment as well as for the state based SoE and yearly reporting.

6 Conclusions

From the policy and legislative perspectives, there is a strong case for investing in the operationalisation of a national earth observation-based inland water quality monitoring program. Existing water quality information across Australia is sparse, difficult to obtain and variable in information content and accuracy. *In situ* data is logistically difficult to collect and may be cost-prohibitive for many areas. An earth observation based method for monitoring is appropriate to Australia where there are large areas of sparse population and limited infrastructure access, and where impacts of increasing pressures from agriculture, mining, urbanisation, irrigation and climate change on inland waters are widespread.

Earth observation can provide temporally consistent and spatially synoptic information on a limited set of water quality variables derived from the reflected light from water bodies. This information may be used to establish environmental baselines as well as for monitoring temporal and spatial change at local to national scales. It can further be used to analyse eutrophication, carbon flow and biodiversity processes. Through data assimilation, the information can be used to inform catchment runoff and inland water quality models.

However, the temporal frequency of earth observation-derived water quality information is limited by satellite overpass frequency, and may be biased by cloud cover. The most readily available sensors for operationalisation of national scale monitoring have limited ability to resolve small water bodies such as narrow river channels.

Australia holds an extensive satellite data archive back to 1984 for 30 m resolution data, and 2003 for 300 m resolution data. This archive, coupled with available and planned satellite sensors, provides the data for a national program that could systematically perform retrospective, current and future inland water quality monitoring.

A top-down hierarchical monitoring program that aligns with the reporting frameworks of the NWQA and SoE reporting would be most suitable for an operational monitoring system. The framework for this hierarchical structure would include:

- Low spatial high temporal resolution earth observation sensors that provide national level reporting. These will enable monitoring of 2,300 water bodies in Australia, representing 2% of the total water bodies on the continent and 11% of the total inland water surface area.
- Medium spatial and temporal resolution earth observations sensors that provide regional, state and river basin reporting. These sensors enable monitoring of 63,000 water bodies in Australia, representing 42% of the total water bodies on the continent and 32% of the inland water surface area.
- High spatial resolution sensors that are suitable for detailed reporting based on regional and local water management agency needs.

Operationalisation of earth observation for terrestrial mapping, inland water *quantity* assessment and coastal water quality monitoring is far advanced. The science of inland water *quality* assessment is well understood. A modest investment in earth observation research and development would achieve a significant advance in Australia's inland water quality monitoring capability.

Physics-based inversion algorithms are apposite for a national inland water quality monitoring program. They are suited for automation, can be applied retrospectively to the existing archive and adapted to present and future sensors, and provide estimates of the confidence of the relevant water quality retrievals. Furthermore, once the algorithms are adequately parameterised using *in situ* bio-optical measurements they should not require repeated *in situ* measurements for further parameterisation.

As with *in situ* programs, transparent validation and error reporting for earth observation-derived inland water quality information products is needed to create confidence with end-users. The data must be reliable, available long term, and in the case of compliance monitoring, be legally defensible.

As illustrated by the case studies in chapter 4, one of the most pressing research and development needs toward operationalising a national system is the need for more *in situ* data for parameterisation and validation of earth observation-derived water quality information products. As water management authorities continue to perform *in situ* sampling to meet their regulatory requirements, opportunities exist for the collection of synergistic *in situ* measurements that provide benefits to improved validation of earth observation approaches and to the water management authorities’ immediate monitoring needs.

7 Recommendations

To achieve the goal of operationalising national inland water quality monitoring using earth observation, investment is recommended in three areas:

1. Capacity building
2. Performing demonstration studies
3. Creating communities of practice and establishing relevant standards and protocols

7.1 Capacity building

7.1.1 SATELLITE SENSORS

Data from three existing satellite sensors should be pursued based on their proximity and suitability to operationalisation and their successor systems being recently launched or intending to be launched:

- MODIS
- MERIS
- Landsat

Significant operational investments have already been made for these sensors, and should be leveraged for an inland water quality monitoring system. GA has invested significantly in operationalising the processing for the Australian Landsat data to normalised reflectance of terrestrial surfaces, providing NBAR corrected imagery. Similarly, significant investments have been made by GBRMPA, CSIRO, IMOS, the Bureau and eReefs for operationalising coastal water quality from earth observation for the GBR Lagoon as a precursor to a national coastal water quality monitoring system using MODIS, MERIS and VIIRS.

Additionally, investments need to be made in the switch over from the existing sensors to new ones (i.e. MODIS to VIIRS, MERIS to OLCI, and Landsat to LDCM). VIIRS was successfully launched at the end of 2011, and LDCM and OLCI will commence in the 2013-2014 period. Although beyond the scope of this report, the investment associated with this development should be evaluated immediately.

7.1.2 RESEARCH AND DEVELOPMENT NEEDS

Although the state of the science is sufficiently advanced to retrieve water quality variables from earth observation data, additional research and development is needed to make such retrievals operational across a range of sensors and water bodies.

Applied research into the following topics should be funded:

- Atmospheric, sun and sky glint corrections need to be developed that are robust and adaptive to the environmental conditions that occur over Australia.
- Characterize the optical variability of inland water bodies. Collect a representative spectral library of inland water bio-optical properties to parameterise and validate physics-based inversion algorithms.
- Investigate scaling effects of *in situ* water quality data versus earth observation-derived water quality information. This includes investigating the possibility of translating *in situ* algal cell counts to earth observation-derived CHL concentrations, and reconciling point-based measurements with pixel-based measurements.

7.1.3 IN SITU MEASUREMENTS

A major conclusion of this report is the need for additional bio-optical information on Australia's inland water bodies. Aligning water management authority routine *in situ* measurements with variables relevant to earth observation will enhance the reliability and usefulness of the earth observation information. Conversely, earth observation information can provide insight into suitable locations for routine *in situ* measurements.

By synchronizing and calibrating routine *in situ* measurements of water management authorities to expert bio-optical measurements, the data can be used for longer term validation of earth observation-derived water quality information. The following recommendations are offered to ensure that ongoing *in situ* sampling programs are more relevant to earth observation and vice versa:

- Timing with earth observation satellite overpasses (typically between 10:00 and 15:00) to obtain sufficient validation data for earth observation –derived water quality information products.
- Discrete sampling includes measurements of CDOM, CHL, CPE, CPE, TSM split into organic and inorganic matter, K_d, Secchi disk transparency and turbidity (NTU).
- Calibrate *in situ* automated continuous physicochemical and bio-optical instruments to discrete *in situ* sampling.

7.2 Demonstration studies

Five demonstration studies should be commenced to address gaps in the operational status of a national water quality monitoring program from earth observation.

1. Thorough validation of earth observation water quality products from one of the water management areas that are closely aligned with the case studies in chapter 4. A study site selected from within the given case studies reduces the investment in this research. A complete characterization of the errors associated with earth observation estimates, the sources of those errors, and the transferability of those errors to new satellite data sources should be examined. Investigation into the scaling effects from the recommendations in 7.1.2 should be initiated in this demonstration study.

2. In a remote area such as the Lake Eyre Basin, establish a climatology of water quality conditions in the basin by analysing the Landsat data archive. This investigation would provide understanding of the impacts of changing flood and drought conditions on these poorly monitored systems, providing insights into the knowledge gaps created by infrequent monitoring programs. This study could be used to trial NWQA and SoE-style reporting for the basin. Findings from this study could be used to inform cost effective monitoring programs in remote areas that capture critical events and processes.

3. Measure the changing water quality conditions under flood conditions such as the Victorian 2011 black water events. Investigation into the water quality conditions before, during and after the event will provide insights into the ecological response to flood events. Critical to this study would be capturing the extreme optical conditions that may occur for parameterisation for future and previous occurrences.

4. Near-surface remote sensing should be investigated as an intermediate scaling step between *in situ* measurements and satellite based earth observation. *In situ* spectroradiometry from boats, jetties or fixed structures can be used to assess water quality using the same physics-based inversion algorithms. A deployment network of continuous near surface remote sensing instruments could be used to complement earth observation-based measurements, addressing temporal gaps in earth observation coverage.

5. A virtual station proof-of-concept study that would process several years or even decades of medium spatial resolution Landsat data nationwide to assess the level to which the 2,300 water bodies measureable by MODIS and MERIS are spatially and temporally representative of Australia's water quality conditions. This study would address:

a. Are virtual stations for water quality a solution for the limitations of *in situ* discrete and permanent automated continuous measurements?
b. How can data be aggregated to broad overviews of water quality for catchment, regional, state and national reporting?

7.3 Standards, protocols and communities of practice

7.3.1 STANDARDS AND PROTOCOLS

- In order to inform the next NWQA and SoE, NWIS standards must be established for earth observation-based CHL, CPC, CPE, CDOM, NAP and K_d.
- To collate a dataset to calibrate and validate earth observation derived water quality information, measurement protocols need to be developed and communicated.

7.3.2 COMMUNITIES OF PRACTICE

Data assimilation

To date there has been no systematic delivery of inland water quality information from earth observation, thus catchment and inland water hydrological and biogeochemical modellers have not considered if and how to incorporate such information into these models. A dialogue should be initiated with modellers of terrestrial and aquatic ecosystems. The dialogue should address how they would use systematic earth observation-derived water quality information.

Multiple use of earth observation data

The current practice of project-based research or applications that focus on mapping catchment vegetation and soil cover, riparian vegetation or water quality should no longer be encouraged. An integrative approach is recommended under which the most suitable satellite data is acquired and processed to allow multiple information products to be delivered across the terrestrial and aquatic domains.

Significant effort is already spent using optical earth observation data for detecting inundation, flood extent and drying. However, there is potential to also assess water quality from the same datasets. The potential for integrated use of optical earth observation data for both water quantity and water quality applications should be investigated. Integration would provide economy of scale for the required earth observation processing infrastructure, making as much use as possible of existing investments by the Bureau, IMOS and TERN in this research and applications area. This approach also provides a framework for priority setting for earth observation-related *in situ* infrastructure investments at state, basin, local, regional and local levels offering a large return on investment and ensuring ease of implementation.

National engagement

Toward an earth observation-based national inland water quality monitoring program, the following national engagement activities are recommended:

- A consortium of earth observation data providers consisting of the Bureau, GA, CSIRO, IMOS, TERN and universities should be created to streamline national data sources, access and future data requirements.
- A working group for the implementation of earth observation for inland water quality. Members might include the Bureau, GA, CSIRO and university groups.
- Workshops involving a representative group of end-users via basin scale to individual lake system based regions to better understand gaps and priorities.
- Present the case for operationalising inland and estuarine water quality at relevant conferences and meetings to inform the community. This case should be supported by demonstration study results.

International engagement

Internationally Australia has to actively engage with the international space agencies that fund, design, build and launch relevant earth observation sensors for assessing Australia's water quality. Australia's contribution to international earth observation infrastructure could be by providing reliable *in situ* data for validation of their satellite data and by providing satellite data reception, archiving and distribution facilities. The national communities of practice should closely liaise with the GEO Working Group on Earth Observation of Inland and Near-Coastal Water Quality to ensure consistency with international developments. A unique capability Australia could offer is providing insight on how to operationalise inland water earth observation across climatic zones ranging from temperate to tropical, and from monsoonal to semi-arid.

Appendix A Amount and area of Australian water bodies detectable from satellites

Table 8-1 Amount of water bodies reliably assessed at MODIS (250m) and MERIS(300m) and Landsat (30 m) resolution

STATE		LAKE	LAND SUBJECT TO INUNDATION	MARINE SWAMP	SALINE COASTAL FLAT	SALT EVAPORATOR	SETTLING POND	SWAMP	TOWN RURAL STORAGE	WATER-COURSE AREA	TOTAL
WA	Total Number	55,088	3,052	119	971	14	63	1,272	92	4,571	65,244
	1000m	313	187	5	50	5	3	7	3	5	578
	120m	6,628	2,901	114	793	15	60	904	81	2,662	14,159
	Total Area(km^2)	38,850	23,775	297	7,709	253	155	612	1,149	4,595	77,401
	1000m	1,1700	4,357	56	2,052	68	23	13	659	45	18,973
	120m	38,109	23,742	293	7,334	192	155	611	1,149	4,216	75,806
NT	Total Number	9,693	4,482	10	2,469	1	18	1,336	27	1,435	19,475
	1000m	66	184	0	78	0	0	49	1	6	384
	120m	2,930	4,151	9	1,663	1	16	1,255	23	544	10,596
	Total Area(km^2)	93,096	241,511	82	68,007	2	150	32,579	10,721	27,696	473,868
	1000m	2,199	4,824	0	598	0	0	971	10	94	8,687
	120m	4,897	14,341	4	3,576	0	10	2,611	46	958	26,445
QLD	Total Number	16,614	4,916	42	1,976	7	68	3,625	1,070	3,325	31,657
	1000m	70	284	0	55	2	1	57	13	7	489
	120m	4,999	4,806	35	1,582	6	53	3,396	891	1,335	17,117
	Total Area(km^2)	5,527	74,438	41	6,092	36	57	4,288	1,509	4,402	96,402
	1000m	1,636	12,311	0	721	3	2	578	202	51	15,504
	120m	3,687	31,582	21	3,431	24	41	2,929	1,051	1,132	43,903
SA	Total Number	18,325	1,485	0	60	24	29	751	38	616	21,332
	1000m	270	136	0	4	4	0	16	0	9	439
	120m	9,471	1,337	0	53	23	20	620	34	367	11,928
	Total Area(km^2)	39,740	21,505	0	288	71	17	540	26	1,897	64,090
	1000m	19,778	1,217	0	12	13	0	52	0	73	21,145

	120m	30,246	5,687	0	198	58	10	360	11	901	37,475
VIC	**Total Number**	2,941	946	37	0	5	40	526	224	145	4,866
	1000m	52	53	1	0	0	1	10	12	0	129
	120m	1,648	883	35	0	5	37	503	153	39	3,303
	Total Area(km^2)	2,402	4,957	57	0	14	36	654	900	420	9,441
	1000m	756	697	1	0	0	1	29	134	0	1,618
	120m	1,878	2,752	27	0	11	25	457	612	5	5,767
NSW	**Total Number**	5,608	2,478	0	1	2	39	1,264	801	759	10,960
	1000m	189	194	0	0	1	0	35	22	0	441
	120m	4,144	2,387	0	1	2	33	1,218	732	410	8,937
	Total Area(km^2)	8,105	40,600	0	1	19	22	3,595	1,421	1,015	54,782
	1000m	2,731	11,155	0	0	4	0	481	135	0	14,506
	120m	7,797	30,595	0	1	19	22	3,507	1,296	884	44,124
TAS	**Total Number**	558	99	35	0	0	4	568	86	112	1,462
	1000m	4	3	4	0	0	0	9	14	0	34
	120m	473	87	35	0	0	4	519	85	11	1214
	Total Area(km^2)	364	101	80	0	0	3	541	1,197	239	2524
	1000m	38	6	9	0	0	0	16	456	0	525
	120m	180	67	55	0	0	1	369	1,032	1	1,706
ACT	**Total Number**	3	0	0	0	0	3	0	9	2	17
	1000m	0	0	0	0	0	0	0	0	0	0
	120m	1	0	0	0	0	2	0	8	1	12
	Total Area(km^2)	< 1	0	0	0	0	< 1	0	13	< 1	13
	1000m	0	0	0	0	0	0	0	0	0	0
	120m	< 1	0	0	0	0	< 1	0	2	< 1	< 1

This table was condensed to Table 3-3 Amount of water bodies that may be resolved by MODIS-MERIS and Landsat resolution in chapter 3.6.

Appendix B A primer on earth observation of inland water quality

This primer is adapted from (Dekker and Bukata, 2002).

B.1 Introduction

Remote sensing is a suitable and valuable technique for large-scale monitoring of inland and coastal water quality, providing synoptic views of the spatial distribution of the biological, chemical and physical variables of both the water and if visible, the bottom surface. Remote sensing of water colour as a determinant of water quality was initially developed for oceans, the optical properties of which are determined solely by phytoplankton and its breakdown products. For these optically relatively simple waters a few spectral bands in the blue to green spectral areas are invariably sufficient to infer chlorophyll concentrations with adequate precision for most oceanographic-biological purposes.

All other waters whose optical properties are determined by components in addition to or other than phytoplankton referred to as optically complex waters. These other optical components are usually a composite of dissolved organic matter from terrestrial origin, dead particulate organic matter and particulate inorganic matter. Also, if bottom reflectance influences the water leaving radiance signal, a water body is considered optically complex, irrespective of other organic and/or inorganic colorants. Phytoplankton is a composite term incorporating a multi-species population of aquatic biota. Due to the single-colorant nature of oceanic waters, workers such as (Bricaud et al., 1999) realised the potential of imaging spectrometry from space for deriving other algal pigments than chlorophyll *a* from oceanic waters. The optical properties of cyanobacterial algal blooms, however, require remote sensing via additional spectral bands at longer wavelengths. Thus, relatively simple band ratio algorithms applicable to clear ocean waters are inappropriate for inland and coastal waters, but also for some algal bloom situations in ocean waters. In this review we will describe water in terms of its optically significant properties and the aquatic matter responsible for those properties.

Research in remote sensing of inland and coastal waters has evolved as a synergistic admixture of theoretical and applied modelling, sensor development, and calibration/validation based on aquatic optics. Many inland and coastal waters are highly affected by anthropogenic influences. In combination with the complex hydrological situation, highly contrasted structures evolve in time and space within these aquatic environments. Obviously, a water system with a variety of optically active substances that display temporal and spatial variations is more complex and requires more sophisticated models for remotely sensing the water constituents than mid-ocean waters containing only one component.

We shall focus on imaging spectrometry as the research tool for monitoring of inland, estuarine, coastal and coral reef aquatic environments. This in no way implies that the operational broader band sensors are of no consequence. In fact, due to their having been operational since 1984 (Landsat TM) and other multispectral satellite systems, vast data archives of remotely-sensed data exist that may potentially be exploited for purposes of trend detection. These broad spectral band satellite sensors are especially good at mapping levels of suspended matter in the water column. However, a discussion of the science of remote sensing is more logical in the context of hyperspectral sensors.

In order to illustrate the direction in which remote sensing of inland and coastal waters is advancing we will present a somewhat capsulated "walk-through" of the science followed by aquatic scientists in their development of models and algorithms to cope with the optical complexities of inland and coastal waters. Satellite sensing of aquatic resources is essentially the monitoring of one attenuating medium (water) through another attenuating medium (the atmosphere), each producing comparable yet unique challenges to remote sensing. The atmosphere will not be considered in-depth here as it warrants separate review by worker(s) expert in atmospheric physics. (Dekker et al., 2001) present an overview of theory and application of hyperspectral remote sensing applied to coastal and inland waters. Consequently, much of the following text is derived from that review.

B.2 Introduction to the theory

The colour of natural water is a complex optical feature, formed by scattering and absorption processes as well as emission by the water column and of reflectance by the substrate. Substrate reflectance (from seagrass, macro-algae, corals, sand, mud, benthic micro-algae etc.) is a function of absorption and scattering and to a lesser degree emission of the substrate materials.

Variations in colour are determined by the content of particulate and dissolved substances that absorb and scatter sky and solar radiation penetrating the water surface. The colours, or more correctly, the water leaving spectral radiances, are masked by the reflection of sun and skylight at the water surface and by extinction and scattering processes in the atmosphere. This exposes bottlenecks in the processing of remote sensing data into water quality maps. To address this bottleneck a careful and precise simulation (e.g., using statistical Monte Carlo photon propagation tracking methods or radiative transfer numerical models) is required of the radiative transfer in the water, at/through the water-atmosphere interface, and in the atmosphere. These simulations are a prerequisite for the improvement or development of algorithms for retrieving the concentrations of selected water constituents. Therefore, the relationship between the in-water optical properties and their concentrations must be known, as well as the density of the substrate for substrate mapping.

Optically active substances can be split into distinct classes based on their optical behaviour. If the inherent optical properties of these substances are sufficiently known, it becomes possible to determine their contribution to water column colour leading to an estimate of their concentration.

For substrates, there is insufficient information on how the optical properties influence the reflectance of substrate materials. Therefore, it is practice to determine the reflectance of the substrate rather than the concentration-dependent absorption and scattering. Water colour carries spectral information regarding the composition of the water column and, if measurable, of the substrate. For the retrieval of different water constituents, as well as substrate cover, from a remotely sensed hyperspectral signal a suite of inversion methods are available, ranging from the often used, but less precise regression methods, through to physics-based inverse methods.

It is possible to model the colour, or spectral reflectance, of a water body once the relationship between inherent and apparent optical properties and concentrations is known. Coupling such information with simulations of the radiative transfer through water and atmosphere leads to simulation of the at-sensor measured radiance. Inversion of this forward simulation model leads to assessment of concentrations and substrate cover. Analytical inversion methods produce better results than empirical or semi-empirical methods that use simple correlation or reasonable band ratios instead of sophisticated optical models. However, the exploitation of information derived from water colour has been impeded by the incapability to deal with the optical behaviour and complexity of water constituents.

Water column optical properties that may be estimated from an optical remote sensing signal are: suspended matter, vertical attenuation coefficients of downwelling and upwelling light, transparency, coloured dissolved organic matter, chlorophyll *a* contents, and even red tides and blue-green algal blooms. If the water column is sufficiently transparent and the substrate is within the depth where a sufficient amount of light reaches the bottom and is reflected back out of the water body maps may be made of seagrasses, macro-algae, sand and sandbanks, coral reefs, and other bottom features (Dekker et al., 2011; Dekker et al., 2001)

B.3 Light in water: the physics

B.3.1 BACKGROUND

The large variation in the concentration of suspended sediments, phytoplankton and coloured dissolved organic matter in many inland, estuarine and coastal waters results in a highly variable light climate. Hence, optical models play a key role in understanding and quantifying the effect of water composition on optical variables obtained from either *in situ* or remote sensing measurements. Physics-based approaches including bio-optical modelling is preferred above (semi-) empirical algorithms that have been the standard for many years in operational applications of remote sensing (and still are for ocean types of water). Many (semi-) empirical algorithms make extreme simplifications regarding water composition, such as the optical domination of one constituent over all the others. There is a wide range of optical models available for water ranging from generic radiative transfer models (e.g., HYDROLIGHT; Mobley and Sundman, 2000) to models based on simple analytical solutions developed for specific waters or conditions. Analytical models have the important advantage that, due to their relative simplicity, they can be solved very quickly. This is of great importance in a remote sensing application where a model must be evaluated at every pixel of an image.

The fundamental principles of all optical processes are incorporated within Radiative Transfer of Energy theory (RTE). RTE explains how the radiometric properties, i.e. the radiance and irradiance, change in the water column due to the optical properties of the medium. What follows is an analytical optical model (after Dekker et al., 2001) that describes the main light processes in both clear and turbid waters, with and without bottom visibility, taking into account highly variable optical conditions in the water column and the substrate as well as a complex geometry of the incident light field and the viewing angles of a remote sensor.

B.3.2 OPTICAL PROPERTIES OF THE WATER COLUMN FOR OPTICALLY DEEP WATERS

This paragraph introduces the optical properties and variables that are relevant for modelling the optical processes in the water column. These optical properties may be summarized as follows:

- The inherent optical properties (IOPs) are the properties of the medium itself (i.e. water plus constituents). Thus, regardless of the ambient light field; the IOPs are measured by active (i.e. having their own light source) optical instruments (Table 8-2).
- The radiometric variables are the basic properties of the light that is measured by passive optical instruments (using the sun as the light source).
- The apparent optical properties (AOP) are combinations of radiometric variables that can be used as indicators for the colour or transparency of the water, for example the reflectance or vertical attenuation coefficients.
- The diffuse inherent optical properties are a combination of IOPs and AOPs and play an intermediate role in the derivation of the analytical model.

B.3.3 THE INHERENT OPTICAL PROPERTIES

The inherent optical properties (IOPs) depend only upon the medium. There are two main optical processes, absorption and elastic scattering, quantified by the absorption coefficient and the volume scattering function, respectively. Their definition is based on a small volume with an infinitesimal thickness illuminated by a narrow collimated beam of monochromatic light.

Elastic scattering refers to scattering of radiation wherein the frequency and polarisation of the scattered photon remains unaltered. Inelastic scattering is scattering in which scattered photons undergo a change in frequency and polarization, thus inelastic scattering is considered isotropic.

Raman scattering within natural waters is an inelastic scattering process, as is stimulated fluorescence from phytoplankton and certain dissolved organic matter wherein visible light is absorbed at one frequency and re-emitted at a lower frequency. Both processes impact water colour and both processes can be similarly modelled.

Elastic scattering is the most important scattering feature of inland and coastal waters, except for the clearest waters. Incorporation of inelastic scattering is warranted for very clear waters, as indeed has already been done in some existing water colour models. Raman scattering is mainly important in clear oceanic waters. Fluorescence models for dissolved organic matter and pigment fluorescence exist, however they are more of a qualitative nature. The difficulty lies in estimating the quantum efficiency of the fluorescence process, in addition to estimating the quenching effect by the same compounds that cause fluorescence.

For most particles in nature the scattering is peaked in forward directions. The volume scattering function depends only on the difference between the scattered directions. From the absorption coefficient and the volume scattering function other IOPs can be obtained, such as the scattering coefficient and the beam attenuation coefficient. It must be kept in mind that the absorption and scattering coefficients are functions of wavelength.

B.3.4 RADIOMETRIC VARIABLES AND APPARENT OPTICAL PROPERTIES

The fundamental optical variable measured by most remote sensing instruments is radiance L. From the radiance a number of other radiometric quantities can be derived, such as the downwelling E_d and upwelling E_u irradiances from which the apparent optical property of reflectance R may be calculated. Explicit definitions of (ir)radiance (as well as expanded details on the optical terms to follow) may be found in any of the textbooks referenced herein. Apparent optical properties (AOPs) depend both on the medium and on the ambient light field, but they display enough regular features and stability to be useful descriptors of the water body. AOPs of consequence are listed and defined in Table 1. Commonly used AOPs are reflectance and vertical attenuation coefficients. The fact that the AOPs are relatively stable and often behave well with depth makes it easier to relate them to the water composition than to (ir)radiance measurements. In particular, the reflectance just below the surface, $R(0-)$, and the diffuse attenuation coefficient for downwelling light, κ_d, are very suitable.

B.3.5 THE DIFFUSE APPARENT OPTICAL PROPERTIES

In addition to the IOPs and AOPs there is an intermediate set of optical properties, called the diffuse apparent optical properties. They describe the absorption and scattering of down- and upwelling irradiance. Most of these properties are only used for mathematical convenience in the derivation of the analytical model. The final model is then rewritten in terms of the IOPs and AOPs, with the exception of the shape factors for upward, r_u, and downward, r_d, scattering functions, since they are not just intermediate parameters, but remain present in the final analytical model. The shape factors 'convert' the backscattering coefficient into the upward and downward scattering functions. Upward scattered photons originate partly from photons that are forward scattered. Since most particles in water scatter more light in forward directions than in backward directions, this contribution can be significant (Stavn and Weidemann, 1989).

Table 8-2 Description and definition of the apparent optical properties

SYMBOL	DESCRIPTION/DEFINITION	UNITS
R	irradiance reflectance $R \equiv \frac{E_u}{E_d}$	- -
$R(0-)$	subsurface irradiance reflectance $R \equiv \frac{E_u(z=0)}{E_d(z=0)}$	-
$R_L(\theta,\phi)$	radiance reflectance $R_L(\theta,\phi) = \frac{\pi L_u(\theta,\phi)}{E_d}$	-
$R_{rs}(\theta,\phi)$	remote sensing reflectance $R_{rs}(\theta,\phi) = \frac{L_u(\theta,\phi)}{E_d}$	sr^{-1}
K_d	diffuse attenuation coefficient of downwelling light $K_d \equiv -\frac{1}{E_d}\frac{dE_d}{dz}$	m^{-1}
K_u	diffuse attenuation coefficient of upwelling light $K_u \equiv -\frac{1}{E_u}\frac{dE_u}{dz}$	m^{-1}
Q	ratio of upwelling irradiance to upwelling radiance $Q(\theta,\phi) \equiv \frac{E_u}{L_u(\theta,\phi)}$	sr
$\bar{\mu}_d$	downwelling average cosine $\bar{\mu}_d \equiv \frac{E_d}{E_{0d}}$	-
$\bar{\mu}_u$	upwelling average cosine $\bar{\mu}_u \equiv \frac{E_u}{E_{0u}}$	-
K_d^{norm}	normalized diffuse attenuation coefficient of downwelling light $K_d^{norm} = \bar{\mu}_d K_d$	m^{-1}

E_d and E_u are the downwelling and upwelling irradiances, $E0_d$ and $E0_u$ are the downwelling and upwelling scalar irradiances, L_u is the upwelling radiance (note: R, E, L and K are all defined spectrally, for reasons of clarity the subscript λ has been omitted).

B.3.6 AN ANALYTICAL SOLUTION OF THE IRRADIANCE RADIATIVE TRANSFER EQUATION (RTE)

Aas (1987) presented a comprehensive analytical solution for the RTE in optically deep waters, where bottom effects can be neglected. Furthermore, it is assumed that the downwelling irradiance decays exponentially with depth (known as Beer's law)

Equation 1

$$E_d(z) = E_d(0-)\exp(-K_d z).$$

Aas (1987) derives an analytical expression for K_d that goes one step beyond the single scattering approximation, since it includes a second order scattering effect in the second term. In clear waters this second term is often neglected: $K_d \approx c_{dd}$

Equation 2

$$K_d = c_{dd} - \frac{b_{du} b_{ud}}{c_{uu} + c_{dd}}$$

Where c_{dd} = local transmittance functions for downwelling irradiance; b_{du} = diffuse downward scattering function for upwelling irradiance b_{ud} = diffuse upward scattering function for downwelling irradiance c_{uu} = local transmittance function for upwelling irradiance.

This analytical model for K_d can be rewritten in terms of the absorption and backscattering coefficients a and b_b. Substituting the relevant definitions in Table 8-2 gives

Equation 3

$$K_d = \frac{a}{\bar{\mu}_d}\left[1 + r_d \frac{b_b}{a}\left(1 - \frac{r_u \bar{\mu}_d}{\bar{\mu}_u + \bar{\mu}_d}\frac{b_b}{a + k b_b}\right)\right], \qquad k = \frac{r_d \bar{\mu}_u + r_u \bar{\mu}_d}{\bar{\mu}_u + \bar{\mu}_d}.$$

To specify the model in Equation 3, four parameters (AOPs) are required, namely $\bar{\mu}_d, \bar{\mu}_u, r_d$ and r_u, where r_u and r_d are the shape factors for up and downward scattering respectively. Unfortunately relatively little is known about the values for the shape factors in turbid waters. In most analytical models the shape factors are set to 1. However, Stavn and Weidemann (1989) find that r_d can vary between 1.3 and 10 and that r_u can vary between 1.8 and 20, during development of phytoplankton blooms in ocean waters. These results indicate that the (variation in the) shape factors must be taken into account. To the best of our knowledge their values have not as yet been determined for turbid water types. Hence, research on the shape factors in these waters is highly recommended.

Equation 3 can be considered as a generic model that is expected to be valid in both clear and turbid waters. In order to compare the concept of Equation 3 with other models found in the literature, it is convenient to neglect the second term in Equation 2 consequently neglecting the latter part of the second term in Equation 3.

Equation 4

$$K_d = \frac{a}{\bar{\mu}_d}\left[1 + r_d \frac{b_b}{a}\right]$$

Several analytical models similar to Equation 4 can be found in literature. For instance, setting the shape factor r_d to 1 gives the model of Walker (1994) and if, in addition, the $\bar{\mu}_d$ is approximated by μ_0 (the cosine of sun zenith) we arrive at the model of (Gordon et al., 1975).

B.3.7 AN ANALYTICAL MODEL FOR THE IRRADIANCE REFLECTANCE

We refer to Aas (1987) for a complete derivation of the analytical model for the irradiance reflectance. The reason for choosing this model is that it can act as a reference for understanding all other models of this kind found in literature. In terms of the backscattering and absorption coefficients the Aas (1987) analytical model for irradiance reflectance can be written as

Equation 5

$$R(0-) = \frac{r_d \bar{\mu}_u}{\bar{\mu}_u + \bar{\mu}_d} \frac{b_b}{a + k b_b}, \qquad k = \frac{r_d \bar{\mu}_u + r_u \bar{\mu}_d}{\bar{\mu}_u + \bar{\mu}_d}$$

Despite this model containing approximations (Aas, 1987) it may be expected to yield quite accurate results for turbid waters. Most studies neglect the variation in the shape factor and use empirical corrections based on the sun zenith angle instead of average cosines. The findings of Whitlock et al., 1981 indicate, however, that for turbid waters the values for the average cosines for downwelling and upwelling light play a significant role. A potential problem is that it is probably impossible to use one set of typical values for $\bar{\mu}_d, \bar{\mu}_u, r_d$ and r_u.

Near the coast and in intertidal areas large temporal variations in turbidity are measured, caused by the large variation in the concentration of suspended particles (from a few to more than 1000 g m^{-3} within one tidal period). Since the optical conditions can be so different it may be necessary to use a two-step approach. First, the IOPs (and subsequently the constituent concentrations) are calculated from the reflectance using a set of average values for $\bar{\mu}_d, \bar{\mu}_u, r_d$ and r_u. Second, using the calculated IOPs as input these four parameters are calculated with a RTE-model such as HYDROLIGHT and then the IOPs are calculated again with these adapted values. It is recommended to investigate the range of values for the average cosine and the shape factors that may occur in inland, estuarine and coastal waters.

Consistent with the above, most optical models focus on relating subsurface spectral volume reflectance R to the water quality properties b_b and a. Relating water colour (be it measured by spectral R or spectral R_{RS}) to the bulk inherent optical properties b_b and a is not the only responsibility of aquatic science (i.e., RTE). The remote sensing products of value to end-users (scientists and resource managers alike) are the co-existing concentrations of organic and inorganic matter that collectively generated R or R_{RS}. As discussed earlier this necessitates knowledge of the spectral behaviour of the specific IOPs of the aquatic matter since additive partitioning can be invoked for every wavelength, namely:

Equation 6

$$a = a_W + x a_P + y a_D + z a_S$$

Equation 7

$$b_b = b_{bW} + x b_{bP} + y b_{bD} + z b_{bS}$$

where a_W, a_P, a_D and a_S are the specific absorption coefficients of water, phytoplankton, dissolved organic matter, and suspended particulates, respectively; b_{bW}, b_{bP}, b_{bD}, and b_{bS} their respective specific backscattering coefficients, and x, y, and z their respective concentrations. (Note: b_{bD} is invariably taken to be zero). Further, it must be remembered that P, D, and S represent a group of optically different substances. Inherent optical properties (IOPs) may display both similarities and dissimilarities in some of their spectral shapes and spectral intensities. These characteristics complicate the extraction of optically active constituent concentrations from a remote measurement of aquatic colour. Cataloguing the spectral IOPs of indigenous colorants (particularly for geologically-diverse inorganic suspended matter and seasonal variable phytoplankton species) needs to be addressed on a global scale. Equations (6) and (7) are clearly multivariate in nature. It can be seen, however, that if a and b_b are known in concert with x, y, and z then the IOPs can be estimated. Similarly, if a and b_b are known in concert with the IOPs, then x, y, and z can be estimated. These determinations comprise the directives of the so-called physics-based approaches including bio-optical algorithms and water quality parameter extraction methodologies.

A variety of complex water quality algorithms have evolved. A prominent early premise was to simply "tweak" models and algorithms that were successful in oceanic waters thereby rendering them appropriate for complex water use. We will not waste time discussing such a premise. However, the converse is far more defendable, namely that algorithms developed for complex waters could, in their simplistic limits, be applicable to oceanic waters. Water quality algorithms are a major topic unto themselves and we do not have the space to discuss them in depth here. Suffice to say that the science is still evolving and the approaches include semi-empirical modelling, non-linear multivariate analyses, principal component analyses, and neural networks, amongst others. Many of these approaches have recently been reviewed by Matthews, (2011) and Odermatt et al., (2012).

OPTICALLY SHALLOW WATERS

Optically shallow waters are waters where the substrate signal is detectable through the water column by a remote sensor. Examples are submerged macrophytes and sandy bottoms in lakes, seagrass and macro-algae fields in estuarine and coastal environments and coral reefs in tropical ocean environments. (Maritorena et al., 1994)summarise and describe the physics of an optical shallow water body where part of the reflectance at the surface is composed of a bottom signal. In optically shallow waters $E_u(0-)$ is the sum of (i) upwelling irradiance originating within the water column (where none of the photons have interacted with the substrate), $E_u(0-)_C$, and (ii) the upwelling irradiance reflected from the substrate (where each of the photons have interacted with the substrate), $E_u(0-)_B$:

Equation 8

$$E_\mathrm{u}(0-) = E_\mathrm{u}(0-)_\mathrm{C} + E_\mathrm{u}(0-)_\mathrm{B}$$

After many manipulations Maritorena et al. (1994) arrive at the following expression for the reflectance just below the surface of a homogeneous water body with a reflecting substrate

Equation 9

$$R(0-, H) = R_\infty + \exp(-K_\mathrm{d} H)[A \exp(-\kappa_B H) - R_\infty \exp(-\kappa_C H)]$$

R_∞ = subsurface irradiance reflectance over a hypothetical optically deep-water column; A = bottom albedo; H = bottom depth; κ_B = vertical attenuation coefficient for diffuse upwelling light originating from the bottom; and κ_C = vertical attenuation coefficient for diffuse upwelling light originating from each layer in the water column. If one is not able to separate the two upwelling light streams, assuming that $\kappa_B = \kappa_C = \kappa$, Equation 9 simplifies to:

Equation 10

$$R(0-,H) = R_\infty + (A - R_\infty)\exp[-(K_\mathrm{d} + \kappa)H]$$

B.3.8 WATER SURFACE EFFECTS

Downwelling irradiance above the water surface will undergo one of two effects. It will either be reflected from the surface itself back into the atmosphere or it will be refracted across the air-water interface into the water. The surface reflected component is an unwanted signal in remotely sensed imagery. The surface refracted component becomes involved in cascades of absorption and scattering. These processes have been known for considerable time, and procedures for their handing have become commonplace. The concepts of refraction, refractive index, internal reflection, sea roughness, sun glint, and wind-induced optics have been successfully explained and modelled by optical oceanographers many decades ago. Subsequent to the historical work of (Cox and Munk, 1954) numerous workers have applied comparable techniques to the removal of surface wave impacts on downwelling solar and sky radiation when remotely sensing natural water bodies from satellite and/or aircraft altitudes. Nonetheless, difficulties still remain in rigorously detailing the transference of radiation through the air-water interface due to wave energy issues that are a function of local climatic conditions.

Water body surfaces show swell, waves and capillary waves with facets of tens of meters to a few centimetres. Although their distribution can be predicted in a stochastic way, the inherent chaotic nature complicates adequate removal of surface reflectance effects. Therefore flight planning of airborne imaging spectrometry campaigns or purchase of high spatial resolution satellite imagery needs to determine the solar zenith angles and azimuths under which (given the field-of-view of the scanner) it is least likely to image sun glint from the water surface. As a rule of thumb, solar zenith angles of 30° to 60° are optimal over water targets and flight paths should be flown at 0 or 180 headings with respect to the solar azimuth. At high latitudes this will mean flying in a short period around noon in summer to achieve a maximal amount of irradiance. At mid-latitudes the flight time will be dependent on the season: as the maximum solar zenith angles increase going from summer to winter-the flight time envelope decreases from approximately 6 to 8 hours surrounding noon to 2 hours surrounding noon. At low latitudes the requirement to fly between 30° and 60° means that solar noon must be avoided to avoid sunspot effects (direct reflectance from horizontal water surfaces into the field-of-view) then a situation arises with two periods one in the morning and one in the afternoon. In a similar fashion care must be taken when ordering high spatial resolution satellite imagery as the new generation of satellite sensors are able to be pointed in space – this is advantageous if sun and sky glint can be avoided but can be detrimental if sun and sky glint are enhanced.

B.3.9 ATMOSPHERIC EFFECTS AND ATMOSPHERIC CORRECTION

Although the physics of atmospheric correction of remote sensing data over waters is essentially the same as for terrestrial targets, there are a few practical differences that need to be addressed. For any water body it is the signal coming from within the water that is the desired signal. On land it is the surface reflected signal that is of interest. For water bodies the surface reflected signal is a signal that is considered as noise, and is composed of the reflected component of diffuse skylight and of the direct sunlight impinging on the water surface. Water bodies generally reflect, as subsurface irradiance reflectance, in a range of about 1 to 15% of downwelling irradiance. The majority of these waters reflect between 2 and 6% of downwelling irradiance. Thus to obtain (say) 40 levels of irradiance reflectance in the range of 2 to 6% reflectance we need a minimal accuracy of atmospheric correction to 0.1% reflectance.

Although many atmospheric correction software packages are available or are included in generic earth observation processing software they only function over land targets. For atmospheric correction over water bodies various models have attempted to extract the unwanted atmospheric signal from water-leaving radiances. These models ranged from overly-simplistically attributing all the atmospheric return to a single nearby infrared wavelength band (often incorrectly assuming the water reflectance to be zero) to generation of "generic" atmospheres diligently generated by practical combinations of air temperature, solar azimuth, land elevation, aerosol density, day of year, cloud profiles, rainfall, atmospheric composition, wind speed, and other obligatory/optional atmospheric parameters such as visibility and meteorological range. A recent development is the use of image-derived information from wavelength bands in the nearby infrared that enables estimation of water vapour in the atmospheric column beneath the sensor. The c-WOMBAT-c method (see (Brando and Dekker, 2003)) is a versatile sensor independent atmospheric correction method that has been applied to many airborne and satellite sensors over many applications and is suitable for application to complex waters

B.4 Concluding remarks

From the mid-nineties onwards, operational examples of multi-temporal deployments of airborne imaging spectrometry systems over, mainly, inland water targets started to happen in The Netherlands, Germany, and Scandinavia. These studies over inland waters were able to deal with the optically deep waters quite well and produced meaningful results for optical water quality variables such as CHL, CYP, CDOM, TSM, K_d and water transparency. The combination of these results into ecological assessment and monitoring is gathering speed rapidly. The bio-optical models for these waters are becoming more sophisticated as well as the instruments for measuring the IOPs and AOPs. Airborne sensors such as the AISA, CASI and others are well-suited for water quality monitoring, due to their flexibility in platform and programmable band sets. In this field we see developments towards more complete models but also towards methods to compute an inversion of an imaging spectrometry scene using either analytical 1 to 3 band inversions, look up tables, using matrix inversion schemes or using neural networks. For turbid estuarine remote sensing, less use has been made of airborne imaging spectrometers due to the very dynamic nature and the often large size of the estuaries. Most of these studies were intended as illustrations or experiments in preparation of using satellite sensors to monitor these systems. As spaceborne imaging spectrometers become available this field of application is likely to evolve very fast.

In the optically shallow waters, developments have been somewhat different as the bio-optical or physical model describing the interaction of light in the water column and on the substrate is more complex than for optically deep waters and is less easily inverted. This inversion is required to produce meaningful maps of water variables or substrate variables. Similar to the developments in the inland waters, but increasingly complex due to the effect of the substrate, more sophisticated inversion schemes are being proposed for bathymetry assessment and for seagrass. For coral reefs most work has been done to characterize the AOPs by establishing spectral libraries of coral reef reflectance. In Dekker et al., (2011) a review of the literature is presented and a comparison of 5 physics-based and one semi-empirical earth observation algorithm for optically shallow water sis presented. The physics-based inversion algorithms outperform the semi-empirical algorithm consistently

As bio-optical and physics based models become more accurate, inversion schemes can become more sophisticated. Simulations of the reflectance spectrum from waters dramatically reduce the requirement for *in situ* measurements in the long term. They also enable pre-flight determination of optimal spectral band configurations for specific tasks. As *in situ* detection and monitoring becomes more expensive (due to rising labour costs) and does not provide spatially comprehensive information, a remote sensing based approach is beginning to make more and more economical sense. It will be necessary to have available local airborne imaging spectrometry systems or the availability of data from space sensors. The fact that the water column is an ever changing medium, both in space and time as well as in reflectance signature, indicates that imaging spectrometry will be the remote sensing instrument of choice for the future for detection and monitoring of optical water quality and substrate variables.

Acronyms

Satellite sensors

ALI	Advance Land Imager on board of EO-1 (TRW/NASA/USGS)
AASTR	Advanced Along Track Scanning Thermal Radiometer (ESA)
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (joint NASA and METI Japan owned sensor)
AVHRR	Advanced Very High Resolution Radiometer (NOAA)
CHRIS-PROBA	Compact High Resolution Imaging Spectrometer on board of Proba-1 satellite platform (ESA)
EO-1	Satellite platform with Hyperion and ALI (TRW/USGS/NASA)
GOCI	Geostationary Ocean Colour Imager (Korea)
GeoEye-1	High spatial resolution sensor owned by GeoEye Corp. (USA)
Hyperion	Hyperspectral sensor on board of EO-1(TRW/USGS/NASA)
IKONOS	High spatial resolution sensor owned by GeoEye Corp. (USA)
IRS	Medium spatial resolution sensor (ISRO, India)
LDCM	Landsat Data Continuity Mission (USGS)
Landsat TM 4, 5	Landsat Thematic Mapper satellites 4 and 5 (USGS)
Landsat 7 ETM	Landsat Enhanced Thematic Mapper (USGS)
LISS-3	Linear Imaging Self Scanner –III (ISRO, India))
MERIS	MEdium Resolution Imaging Spectrometer (ESA)
MODIS	MODerate resolution Imaging Spectrometer (NASA)
OCM-2	Ocean Colour Monitor-2 (ISRO, India)
QuickBird	High spatial resolution sensor owned by Digital Globe Corp. (USA)
Rapid Eye	High spatial resolution sensor by RapidEye AG (Germany)
SeaWiFS	Sea-viewing Wide Field of view Sensor (first NASA then Orbital Image Corporation now GeoEye Corp.)
Sentinel-2	Multispectral 10/20/60 m resolution sensor (ESA)
Sentinel-3	Multispectral 300 m Ocean and Land sensor (ESA)
SPOT-4	Système Pour l'Observation de la Terre = System for Earth Observation
SPOT-5	----Owned by SPOT Corp. (France)
SPOT- 6 & 7	----id-----
VIIRS	Visible /Infrared Imager Radiometer Suite (NASA/NOAA)
WorldView-2	High spatial resolution sensor owned by Digital Globe Corp. (USA)
WorldView-3	High spatial resolution sensor planned by Digital Globe Corp. (USA)

Airborne imaging spectrometers

AISA	Airborne Imaging Spectrometer for environmental Applications (by Specim, Finland)
CASI	Compact Airborne Imaging Spectrometer (by ITRES, Canada)
ROSIS	Reflective Optics Systems Imaging Spectrometer (by German Aerospace Laboratories, Germany)

Space agencies

ESA	European Space Agency
ISRO	Indian Space Research Organisation
METI	Japan's Ministry of Economy, Trade and Industry
NASA	National Aeronautics and Space Administration (USA)
NOAA	National Oceanographic and Atmospheric Administration (USA)
TRW	Aerospace company (part of Northrop Grumman)
USGS	United States Geological Survey

Other acronyms

ANZECC	Australian and New Zealand Environment Conservation Council
AOP	Apparent optical properties (e.g. vertical attenuation coefficients and reflectance)
AWRA	Australian Water Resources Assessment
BEAM	Open source toolbox and development platform for viewing, analysing and processing of remote sensing raster data
BRDF	Bi-directional reflectance distribution function
c-WOMBAT-c	Coastal Waters and Ocean MODTRAN-4 Based Atmospheric Correction method
COAG	Council of Australian Governments
CDOM	Coloured (or chromophoric) dissolved organic matter
CHL	Chlorophyll
ChloroGIN	Chlorophyll Globally Integrated Network
CPE	Cyano-phycoerythrin
CPC	Cyano-phycocyanin
CSIRO	Commonwealth Industrial and Scientific Research Organisation
CYP	Cyano-phycoerythrin and/or cyano-phycocyanin
DO	Dissolved oxygen concentration
EC	Electrical conductivity
EPBC Act	Environmental Protection and Biodiversity Conservation Act (1999)
EOS-SIP	National Earth Observations from Space Strategic Infrastructure Plan
GA	Geoscience Australia
GBR	Great Barrier Reef

GBRMPA	Great Barrier Reef Marine Park Authority
GEO	Group on Earth Observations
GIS	Geographic Information System
HPSC	High Performance Scientific Computing facility
K_d	Diffuse attenuation coefficient for downwelling irradiance
IMOS	Integrated Marine Observing System
LJCO	Lucinda Jetty Coastal Observatory
IOP	Inherent optical properties
MDBA	Murray Darling Basin Authority
MODTRAN	MODerate resolution atmospheric TRANsmission method
NAP	Non algal particulate matter
NBAR	Nadir BRDF-Adjusted Reflectance
NCI	National Computing Infrastructure
NPEI	National Plan for Environmental Information
NTU	Nephelometric turbidity unit
NWI	National Water Initiative
NWIS	National Water Information Standards
NLWIS	National Land and Water Information System (Canada)
NWQMS	National Water Quality Management Strategy
pH	Measure of alkalinity or acidity
RAMSES	*In situ* hyperspectral radiometer
RTE	Radiative Transfer of Energy theory
SD	Secchi disk transparency
SEWPaC	Department of Sustainability Environment Populating and Community
SKM	Sinclair, Knight and Merz Consulting (Australia)
SoE	State-of-the Environment activity and Report by SEWPaC
SPM	Suspended particulate matter (~ TSM and TSS)
TERN	Terrestrial Ecosystem Research Network
TN	Total nitrogen concentration
TP	Total phosphorous concentration
TSM	Total suspended matter (~SPM and TSS)
TSS	Total suspended solids (~SPM and TSM)
VISAT	Software in BEAM for visualization and processing of remote sensing raster data
WFD	Water Framework Directive (European Union)
WIRADA	Water Information Research and Development Alliance

Glossary

Bathymetry	Depth from water surface to bottom of water body
Bio-optical	Relating to light properties in water as a function of dissolved and particulate organic and inorganic matter
Coloured dissolved organic matter	The absorbing substances in water that passes a filter typically of 0.2 µm pore size; CDOM comprises a significant fraction of the dissolved organic matter pool in natural waters
Cyano-phycoerythrin	Accessory photosynthetic phycobilin pigment of cyanobacteria with an *in vivo* absorption peak at 565 nm
Cyano-phycocyanin	Accessory photosynthetic phycobilin pigment of cyanobacteria with an *in vivo* absorption peak at 624 nm
Diffuse attenuation coefficient for downwelling irradiance	A measure of attenuation of downwelling natural light in the water column
Earth observation	energy measurements made from aircraft or satellites
Harmful and toxic algal blooms	Algae that are nuisance forming, harmful or toxic
Inherent optical properties	Light absorption and scattering properties of water and its constituents that are independent of the ambient light field
Macrophytes	Aquatic plant that is emergent, submerged, or floating
Nadir	From the satellite sensor looking vertically down
Non algal particulate matter	The total suspended matter minus the algal biomass
Physicochemical	Related to physical and chemical properties such electrical conductivity, temperature, salinity, density etc., that are measured by non-optical methods
Primary production	The production of organic compounds from aquatic carbon dioxide via photosynthesis
Remote sensing	All reflected and emitted energy measurements where there is a distance between a sensor and the object or material measured (includes earth observation and *in situ* above water spectroradiometers etc.)
Swath	The width of the track that a satellite images as it passes over the earth’s surface
Total suspended matter	The suspended matter obtained by filtering natural waters over a 0.7 to 0.2 µm filter

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