A Synthesis of Remote Sensing Capabilities with Specific Reference to the Business Needs of the Murray Darling Basin Authority

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In partnership with the Murray Darling Basin Authority
Final Report
9 August, 2013

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University of
New England

Published by the Cooperative Research Centre for Spatial Information.

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This report may be cited as: *Tickle, P., Southwell, M., Mitchell, A., and Lowell, K., (2013). A Synthesis of Remote Sensing Capabilities with Specific Reference to the Business Needs of the Murray Darling Basin Authority. Cooperative Research Centre for Spatial Information, Carlton, Victoria.*

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Acknowledgements

The authors would like to thank the MDBA staff for supporting the project and their contributions through numerous internal discussions and workshops. In particular, Alan Forghani, Michael Wilson, Jason Alexandra, and Fraser MacLeod. This report has drawn on, and attempted to synthesise an enormous wealth of information from previous reviews, current literature, knowledge and experience from specialists in Australia and internationally. The authors have made all reasonable efforts to ensure that work is appropriately acknowledged. We sincerely thank workshop participants, and numerous research, State and Australian Government colleagues for their valuable contributions and critical comments and input during the drafting of the report.

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1. EXECUTIVE SUMMARY

The Murray Darling Basin Authority (MDBA) was established under the federal Water Act 2007 to support the sustainable and integrated management of the water resources of the Murray-Darling Basin in a way that best meets the social, economic and environmental needs of the Basin and its communities. The MDBA leads the planning and management of Basin water resources, and coordinates and maintains collaborative long-term strategic relations with other federal, state and local government agencies; industry groups; scientists and research organisations.

Delivering a healthy working Basin requires the integration of social, economic and environmental objectives based on the best available information and knowledge. Over the last decade the MDBA and its predecessors have made significant investments in remote sensing and related technologies in the development of the Basin Plan, and the delivery of numerous projects and programs. However, while the benefits of remote sensing technologies have long been recognised by the MDBA, and indeed incorporated into some existing monitoring programs, the full capabilities over a range of spatial and temporal scales, have not been fully embraced within a holistic monitoring framework.

This report provides an independent and critical appraisal of the current and future potential of remote sensing and related capabilities to contribute to the key business and information needs of the Murray Darling Basin Authority. Through a series of workshops internal to MDBA, 20 primary business and information needs were identified, that may be addressed by remote sensing. For analysis purposes, and to allow the findings of this report to be easily aligned with broader requirements, these primary needs were analysed according to metrics associated with the National Framework for the Assessment of River and Wetland Health (FARWH), with some additions where necessary. A review of previous studies undertaken by the MDBA, recent published and unpublished literature, and current operational programs in Australia was undertaken. In addition, a technical workshop that included external experts, and further consultation with State jurisdictions, were utilised to assess the feasibility of remote sensing to inform the primary business and information needs of the MDBA.

There is clearly significant potential for remote sensing and related technologies to play a greater role in the Murray Darling Basin Authority's operations, and in many cases, to provide a more cost-effective, efficient and transparent means of achieving specific agencies business and information needs. Importantly, there is no single solution and remote sensing technology must be employed in the context of an overarching strategic framework that addresses internal and external needs and reporting requirements of the Basin Plan. Information is required at a range of spatial and temporal scales, and requires a commitment to a suite of technologies, infrastructures, methods, skills and knowledge (i.e. people) to take full advantage of available opportunities, now and into the future.

Key Findings

The review and synthesis has identified the following key findings in relation to the use of remote sensing to contribute to the business and information needs of the Murray Darling Basin Authority.

1. For the potential of remote sensing to be fully realised its use must be placed within the broader context of a whole-of-basin monitoring plan, and adaptive management system.

2. There are significant opportunities for existing state and national programs to address MDBA business needs.

3. There are a number of existing methodologies and datasets that could be extended to produce consistent remotely sensed products across the Basin.

4. Long term commercial service level agreements may offer more cost-effective and efficient mechanisms for acquiring and processing data related to specific events within the basin.

5. Rapidly emerging capabilities require an ongoing commitment to applied research and development to realise the full potential of remote sensing in relation to MDBA business and information needs.

Physical Form

The information needs identified by the MDBA relating to physical form revolve around gaining an understanding of the morphology of the floodplains and flow paths of the basin to provide reliable predictions and models of inundation extent and duration throughout the river systems of the basin. Information is required from the site to valley scale, and temporally from event to annual time-scales.

Mapping of flood extent, floodplain extent and open water mapping are largely operational capabilities that can be carried out using time-series Landsat and MODIS data inputs, or commercial optical and SAR platforms, and simple analytical techniques. Characterisations of the floodplain in terms of wetland habitat, meso-habitat diversity are also feasible using a combination of LiDAR and optical remote sensing but would require pilot studies to develop consistent methodologies.

The majority of metrics associated with physical form require a high resolution digital elevation model (DEM). Airborne LiDAR provides an operational capability to generate DEM's with absolute vertical accuracy generally exceeding 30cm. Metrics such as hydrologic connectivity, channel form, and levees can readily be achieved. The Victorian Index of Stream Condition (ISC) Program has developed automated methods for deriving physical form metrics over Victoria's 28,000km of major watercourse, and provides an operational benchmark for Australia. This initiative has also demonstrated the ability to map in-stream course woody debris and snags using visual interpretation of high resolution imagery. With significant investment in LiDAR continuing in other jurisdictions, we would recommend the application of the ISC metrics and methods, across the basin to form a consistent baseline for reporting and ongoing monitoring.

While airborne LIDAR provides exceptional baseline information and with extensive coverage satisfies the site-valley scale need for information, the ongoing expense of monitoring using wall-to-wall mapping techniques may be problematic. There may however, be opportunities to identify significant areas of change using optical time-series to target future acquisitions, or to use simplified sampling approaches adapted from the SRA.

Water Quality

There is a need to monitor water quality variables in relation to ecosystem, and human or stock health aspects. There is a need for standard water quality metrics such as TSM, salinity, pH, CHL pigments, cyanobacterial pigments, CDOM, K_d and derived variables such as Secchi disk transparency and turbidity at valley scales on an event to seasonal basis. There is also a need to monitor larger scale algae and blackwater events at the floodplain and valley scale, and in particular to provide timely and accurate advice to the community on the movement of these events for future management.

At present a number of water quality metrics can feasibly be monitored using optical satellite or airborne data. These include: chlorophyll-a, CDOM, turbidity, Secchi disk transparency and temperature. Given the relatively small and narrow nature of most of Australia's water bodies, high resolution optical satellite data is generally required. However, the extraction of water quality information is hampered by water turbidity, prevailing weather conditions, bias in temporal observations (due to cloud, haze, smoke, dust etc.), water shading by overhanging vegetation, and a lack of bio-optical information for parameterisation and validation.

The mapping of algae and blackwater events can readily be mapped and monitored using optical satellite data. The most significant challenge relates to the timely acquisition of data to capture the events which can largely be overcome through tasking of commercial satellites, notwithstanding issues associated with cloud cover which often occur during flood events. Victorian and NSW attempt to overcome this using airborne imagery that can often be acquired under the cloud.

Future satellites such as Sentinel-2, Sentinel-3 and the ENmap hyperspectral satellite will provide new opportunities for satellite-based monitoring of water quality. Although the state of science is sufficiently advanced to retrieve water quality variables, additional applied research and development is required to make such retrievals fully operational across sensors and water bodies. Priorities include robust and adaptive corrections for environmental conditions; characterisation of optical variability of inland water bodies; scaling effects of in-situ monitoring verses remote sensing derived water quality information, and thorough validation of water quality products.

Aquatic Biota

Measuring the past and present ecological condition and response of aquatic biota (including fish, birds and vegetation) to flooding within the basin is core to the information needs of the MDBA. Assessing the ecological benefits of environmental watering and works and measures that have been undertaken in icon sites as part of the The Living Murray (TLM) program and more broadly for the assessment of the Basin Plan is also required. Improved modelling capabilities are also required to better predict, plan and evaluate the ecological responses to environmental watering.

Remote sensing can contribute in relation to vegetation metrics including cover of macrophytes, aquatic weeds, and riparian and floodplain vegetation extent, type and structure. Information is generally required at site to reach scales and in relation to specific assets on an event and seasonal basis.

The often narrow extent of macrophytes and riparian vegetation often precludes the use of moderate resolution imagery for aquatic biota. However, mapping the riparian vegetation extent, density, canopy complexity and fragmentation is an operational capability using high resolution optical satellite or aerial imagery.

NSW has completed state wide mapping of woody vegetation extent and density (foliage projective cover) using SPOT5 2.5m imagery. The scale of watercourse mapping across the state varies from 1:25,000-1:100,000 scale. Additional work is required to extract the riparian components of the state wide mapping. The Victorian Index of Stream Condition (ISC) Program has mapped the states' major river systems with LiDAR and high resolution aerial imagery to produce detailed water course, riparian vegetation extent and structural mapping. The NSW and VIC products effectively map at the scale of individual tree canopies. Additional high resolution satellite and aerial imagery, and LiDAR are being acquired in NSW and QLD. With a relatively small investment, there is a significant opportunity to bring together a consistent baseline riparian vegetation extent product over the entire basin at the scale of individual canopies that would underpin other vegetation type and condition products.

While mapping riparian vegetation type in terms of species composition has been demonstrated as feasible in some studies using imagery sources alone, currently the most reliable and operational methods rely on a combination of site data, optical imagery and LIDAR, environmental predictors such as climate, terrain and soils, models of species distribution and expert knowledge and rules. Currently all basin states use variations of this approach, with varying degrees of automation. NSW has completed Plant Community Type (PCT) mapping for a number of catchments including the Murray and Namoi. VIC has completed detailed Ecological Vegetation Class Mapping of the riparian communities as part of the Index of Stream Condition Program. VIC is also now extending the mapping state wide using 5m resolution RapidEye satellite imagery and the EVC modelling approach.

Given the substantial investment in these approaches by all Basin States, there would be significant merit in investing in additional work to produce a consistent floodplain and riparian vegetation type product across the basin, using these methods. Such a product would assist with planning of environmental watering, and underpin ongoing monitoring of ecological condition and responses to flooding.

Predicting, planning and evaluating the ecological response of assets to environmental watering requires the ability to quantify relevant changes in ecosystem condition over time, and ideally the ability to un-mix seasonal variability from management interventions. The Stand Condition Tool which uses Landsat-derived canopy reflectance variables to predict stand condition based on reference field sites has been successful in mapping the canopy condition of Red Gum and Black Box within Icon sites. New capabilities to analyse the entire Landsat time-series data provide the opportunity to explore the development of reference condition metrics derived from the entire time-series, and to reduce the reliance on coincident collection of field data for basin wide application. These stand condition products derived from moderate resolution Landsat data would be improved substantially by constraining the analyses to a riparian and floodplain extent and type product derived from high resolution data.

Importantly, optical remote sensing techniques are generally only suitable for assessing changes in the vegetation canopy, and in sparse canopies can be confounded by seasonal changes in understorey stratums. Analysis of the full times-series optical data is likely to assist in discriminating canopy and understory components, and should be the focus of applied research in the near future.

The development of standard time-series condition metrics needs to be supplemented and supported by establishment of long-term ground reference sites, and strategic acquisition of LiDAR and very high resolution optical imagery to quantify: changes in overstorey and understorey structure, species composition, and reproductive potential.

Future hyperspectral sensors such as EnMAP have the potential to greatly improve monitoring of foliar chemistry, water requirements and routine condition assessment.

Hydrological Disturbance

The information needs of the MDBA relevant to hydrological disturbance relate to changing surface water and ground water flow regimes, and the extent to which these factors influence biotic communities. In terms of remote sensing capabilities, this may be related to the estimation of floodplain harvesting and losses from evapotranspiration (ET), improving characterisation and understanding of surface–ground water connectivity, and monitoring groundwater use outside of currently monitored areas. Losses resulting from floodplain harvesting and ET are at present inadequately accounted for in the MDBA’s hydrological models. More robust knowledge of these losses would also help in the areas of compliance and accounting of water resources in the basin.

Information is required at the site/reach, asset, floodplain and valley scales over event, seasonal and annual timescales. Improved understanding of surface-ground water connectivity would also provide more reliable estimations of recharge, underground connections and aquifer storage. Information at broader spatial scales (valley to basin) over seasonal and annual timescales is also required. Similarly, more comprehensive monitoring of groundwater use at valley and basin spatial scales over seasonal and annual timescales is required to provide more robust accounting of this resource.

Water loss from evapotranspiration (ET) can be reliably estimated using satellite multispectral data, and thermal resistance energy balance modelling approaches such as SEBAL/METRIC. These methods have demonstrated their feasibility for operationally quantifying irrigated crop water use and demand; facilitating improved water use at farm scales; assessing the regional impacts of sustainable diversion limits on cropping and environment assets at catchment scales in VIC. Internationally these methods are also used operationally for compliance and accounting purposes.

Open water likelihood (OWL) mapping is feasible using fused or blended time-series moderate (e.g., Landsat) to coarse (e.g., MODIS) resolution optical data. Satellite derived metrics, such as albedo, emissivity, LAI and vegetation indices provide operational inputs to water balance modelling such as the Australian Water Resources Assessment (AWRA) System. Current models are limited to 5km resolution, and by their relatively simple representation of the groundwater term and dynamics, which is often inadequate for capturing long term response and interactions with surface water and ecosystems at regional to local scales. Further research is required to develop groundwater models and incorporate satellite derived estimates of vegetation cover and soil moisture into existing, and higher resolution water balance models.

Information on groundwater levels and dependent ecosystems is required for improved characterisation of ground-surface water connectivity and monitoring groundwater levels and use outside of currently monitored areas. Current capability is limited, and only a few studies have attempted to predict ground water dependent vegetation and total water storage.

Catchment Disturbance

The information needs of the MDBA in relation to catchment disturbance are largely centred on assessing baselines, trends and potential changes in land cover, land use, land management, vegetation type, extent, condition on river and wetland extent and condition, and the biota. Inputs are required for hydrological models to inform potential changes to groundwater recharge/discharge through interception and bushfire risk, and also to assist with longer term development of water sharing plans. Information is predominantly needed at valley to basin spatial scales and monitored over annual timescales, noting the seasonal nature of some land use and management practices (e.g. double cropping).

The use of remote sensing for land use and management is now well developed. There are well established programs in all basin states through the Australian Collaborative Land Use Mapping Program (ACLUMP) using a combination of cadastral information, digital analysis, visual interpretation, and field validation to reliably map land use to a consistent standard. All of these programs are currently operating on minimal budgets which limit the frequency of updating due to the need for manual intervention.

Geoscience Australia have developed operational methods with time-series MODIS data to map annual changes in broad land cover types at regional to national scales, and the National Carbon Accounting System provides annual forest cover products. Access to the full Landsat time-series and the necessary computing capacity will undoubtedly improve mapping accuracy and reduce change ambiguities.

Methods to describe woody vegetation structure using remote sensing are well developed. Forest cover is routinely mapped using time-series optical satellite data by State agencies and the NCAS. The recent development of fraction cover time-series products (fractional photosynthetic, non-photosynthetic, bare ground and water) is providing numerous opportunities to improve landscape monitoring of woody vegetation, and changes in ground cover and land cover at a range of spatial and temporal scales on an operational basis. Landsat annual and seasonal time-series products are being routinely generated in QLD and NSW and could easily and cost-effectively be extended across the basin.

NSW has completed state wide mapping of woody vegetation extent and density (foliage projective cover) using SPOT5 2.5m imagery annually between 2004-2012, and VIC are commencing a state wide forest cover product using 5m resolution RapidEye. With a relatively small investment, there is a significant opportunity to bring together a consistent woody vegetation extent and density (foliage project cover) product over the entire basin at the scale of individual canopies that would underpin other vegetation type and condition products.

Other measures of forest structure including tree height, stand volume, basal area and biomass are generally feasible or operational using combinations of field survey, LIDAR, SAR or optical imagery at appropriate resolutions. Tree height and density is readily retrieved using airborne LiDAR. Stand volume, biomass, basal area and stem density can also reliably be retrieved by LiDAR and SAR by establishing empirical relationships with field data, although the cost over large areas may be limiting. The Joint Remote Sensing Research Program led by QLD DSITIA and TERN AusCover have commenced a project to develop a national woody vegetation biomass map using ALOS PALSAR and Landsat-derived foliage projective cover. The P-band BIOMASS SAR satellite mission planned for launch in 2016 also provides opportunities for cost effectiveness monitoring of biomass at catchment scales.

The mapping of species composition and vegetation associations, and wetland types, currently and in the near future, requires an integrated approach. State jurisdictions have developed operational techniques utilising time-series remote sensing, environmental predictors such as climate, terrain and soils, models of species distribution and expert knowledge and rules. Currently all basin states use variations of this approach, with varying degrees of automation. NSW have developed a very rigorous Plant Community Type (PCT) mapping methodology, and recently completed a number of catchments including the Murray and Namoi. VIC is also now extending the mapping state wide using 5m resolution RapidEye satellite imagery and the EVC modelling approach. Given the substantial investment in these approaches by all Basin States, there would be significant merit in investing in additional work to produce a consistent vegetation type product across the basin, using these methods. Such a product would assist with planning of environmental watering, underpin development of hydrological models and ongoing monitoring of ecological condition in response to catchment disturbance and responses to flooding.

Monitoring of disturbances relating to fire and storm damage are operational capabilities with MODIS fire and vegetation index products routinely produced by Geoscience Australia, States and international agencies. These capabilities will no doubt improve with the ability to process and analyse the full time-series of Landsat data through Geoscience Australia and the National Computing Infrastructure.

The development of standard time-series condition metrics needs to be supplemented and supported by establishment of long-term ground reference sites, and ideally, strategic acquisition of LiDAR and very high resolution optical imagery to quantify: changes in overstorey and understorey structure, species composition, and reproductive potential over time.

Socio-economic

Given the focus of the MDBA on balancing social, economic and environmental factors with regards to water reform in the Murray Darling Basin, many of the information needs identified were associated with assessing the socio-economic change resulting from water reform.

Data related to irrigated cropping, irrigation frequency, seasonal changes in crop types and over abstraction can be provided using many of the feasible or operational capabilities described in the hydrological and catchment disturbance sections. Given seasonal and market dynamics can drive cropping decisions, time-series remote sensing techniques are required. The dynamic land cover methods developed by Geoscience Australia to analyse time-series MODIS data have demonstrated the ability to reliably detect irrigated cropping, cropping frequency and seasonal changes in irrigated and non-irrigated cropping. Access to the full Landsat time-series and the necessary computing capacity will undoubtedly improve mapping in the future at floodplain to farm scales.

Monitoring irrigation water demand and potential over extraction by irrigators is feasible using satellite multispectral data, and thermal resistance energy balance modelling approaches such as SEBAL/METRIC. These methods have demonstrated their feasibility for operationally quantifying irrigated crop water use and demand; facilitating improved water use at farm scales; assessing the regional impacts of sustainable diversion limits on cropping and environment assets at catchment scales in Victoria. Internationally these methods are also used operationally for compliance and accounting purposes.

Information on the distribution of water harvesting and storage structures, industries and plants can be reliably mapped and monitored using very high resolution optical imagery. Current state and national topographic mapping programs capture this information, including information on the urban environment using visual interpretation techniques. Local governments in most urban centres acquire high resolution aerial imagery in partnership with State governments on a periodic basis as part of ongoing planning and regulation responsibilities. Contributing to these acquisitions and collaborating with State topographic programs will secure cost-effective access to the necessary data to meet MDBA needs.

Environmental Flows

Effective planning for environmental releases to achieve site-scale ecological targets and environmental outcomes relies on accurate flow/inundation models and a sound understanding of the current extent, condition and needs of the assets being managed. It also requires the ability to monitor ecosystem responses to support the evaluation of ecological outcomes arising from environmental watering events.

In addition to needs associated with current ecosystem condition; ecological response to environmental flows; flow/inundation models, and flood extent mapping summarised in previous sections, there are a number of additional specific needs of environmental flows discussed below.

Being able to determine the flooding of land associated with natural flows versus managed flows is an important need for the Authority especially in terms of liability for the flooding of private land. Improved measurement and monitoring of releases and extractions from storages and river channels is needed to ensure precise compliance and accounting of river operations. Knowledge of the antecedent catchment and floodplain conditions is also required for better prediction of flood timing and inundation extent and duration at site to valley scales and from individual events to seasonal and annual timescales.

Current operational methods for estimating soil moisture are limited to assimilation of satellite derived estimates using water balance models to arrive at antecedent basin conditions.

Soil moisture has been estimated from remotely sensed data, however, at coarse resolution, which may not be particularly useful as input into hydrological modelling. Future dedicated soil moisture mapping missions, including SMAP, and future L-band SARs such as SAOCOM will improve the capacity for soil moisture estimation. The development of techniques for remotely estimating soil moisture is also severely hampered by a lack of suitable field data. New low-cost soil moisture probes equipped with data loggers of telemetry systems offer opportunities for better quantifying the spatial and temporal variability in soil moisture, and the data needed to develop remote sensing methods in the future.

The most effective method for deriving water depth and height information in turbid waters is multi-beam sounder or sonar data. An alternative approach is to derive water height and depth information by acquiring LiDAR or photogrammetric data to produce an accurate DEM in drought conditions, when minimal water is in the channel. Then by mapping the extent of future inundation, water height and depth can be derived through simply analyses.

Mapping of flood extent has been demonstrated as an operational capability using airborne and satellite SAR and optical data. However, monitoring flood extent within the context of environmental flows may differ significantly from natural or emergency flood events, notwithstanding the fact that piggybacking on natural high flows is also an effective means of delivering environmental flows. If information on the extent, timing and duration of flooding from environmental flows is seen as critical, tasking abilities offered by numerous commercial optical and SAR providers are necessary. Using either very high resolution satellite optical or SAR platforms daily acquisitions are possible, and in key areas airborne platforms can acquire data on demand.

Environmental Watering Plans and Annual Water Plans define the assets being targeted; the area to be flooded, and the approximate timing of potential events, both in terms of the season and the potential delay from water release to inundation. On an annual and seasonal basis the MDBA therefore has a reasonable understanding of the number, location, duration and planned extent of flooding events. It is therefore possible to develop commercial service level agreements within known budget parameters to cost-effectively acquire and process the necessary data on-demand.

Even with major investment in LiDAR DEMs for accurate flow and inundation modelling, overland flow and drainage may be subject to minor man-made changes such as levees and drains which have a major impact on flood extent and duration. In the event that the significant physical changes occur such as levees which may impact on flows, it is also entirely feasible to update the LIDAR DEM using ground survey, rather than re-flying the entire area. Analysing the differences between planned and actual flood extent could be used to target locations where the LIDAR DEM can be improved using ground survey data.

Environmental Monitoring System Design

The opportunities for current and rapidly evolving remote sensing capabilities to address MDBA business needs are considerable. However, for the potential to be fully realised the use of remote sensing must be placed within the broader context of a whole-of-basin monitoring system. The monitoring system must form an explicit component of the agency's adaptive management approach, and ideally, be based on the following principles:

- Clearly defined outcomes based on strategic goals and information needs to meet these goals.
- Clearly defined objectives and questions which link the strategic-tactical operation requirements and the target audience, and define the minimum level of detail required to produce fit-for-purpose information (information products).
- A sound conceptual model of the Murray Darling Basin and an understanding of the most important environmental indicators; anthropogenic elements; external drivers and the interactions among them.
- An appropriate sampling design and analysis framework that involves targeted, surveillance and landscape monitoring. This design must take account of the full range of spatial and temporal scales; sampling intensity, and the most cost-effectiveness methods and technologies.
- A long-term commitment to resourcing, maintenance and development.
- Reporting to satisfy internal management and policy needs and external queries and certification or compliance.
- Adaptability to external conditions and priorities, changing regulatory constraints and evolving technologies, techniques and knowledge.
- In-built monitoring and system evaluation to ensure the system is meeting needs in a cost-effective and timely manner.
- Collaboration and integration across state boundaries and organisations which minimises duplication and maximises and rewards collective investment.

Potential Collaborative Opportunities

One of the greatest challenges facing the MDBA is engaging the State agencies, Catchment Management Authorities (CMA's) and local stakeholders and fostering a collaborative environment for sharing data and knowledge to support sustainable management and wise use of the MDB. The cooperation of the various interest groups is paramount to ensuring the protection, maintenance and restoration of the basin's biophysical resources now and into the future. Given the demonstrated benefits of geospatial data to contribute to monitoring, evaluating and reporting on basin assets, there is an urgent need to secure ongoing access to data and information products through coordinated co-investment, and partnerships for developing and implementing long-term operational programs that meet the critical business and information needs of the MDBA and others through mutually beneficial partnerships.

There are currently a number of major remote sensing initiatives in Australia that are clearly demonstrating the ongoing operational benefits of monitoring systems based on many of these principles. These existing programs have the potential to contribute directly to the MDBA's business needs. In particular, these programs include: QLD, NSW, VIC and SA high resolution imagery and LiDAR acquisition programs, National Carbon Accounting System (NCAS), the QLD and NSW SLATS and ground cover programs, NSW and VIC vegetation mapping programs, the VIC Index of Stream Condition Program, the Australian Water Resources Assessment Program, the VIC DPI irrigated crop water use program, TERN AusCOVER, The Dynamic Land Cover Mapping Project and the federal Unlocking the Landsat Archive initiative.

Significant opportunities therefore exist for formally coordinated, joint investment in high resolution data acquisition, collaborative processing of time-series data and tailored information products, investment in computing infrastructure and development of on-line processing and reporting capabilities, development of consistent vegetation type, extent and condition mapping across state borders, and ongoing applied research.

2. INTRODUCTION

The Murray-Darling Basin is the largest river basin in Australia, covering more than one million square kilometres, or 14% of Australia. It stretches across five states and territories including Queensland, New South Wales, Victoria, South Australia and the Australian Capital Territory. The sustainable management of the Basin's water resources poses one of the most urgent and complex challenges of our time.

The Murray Darling Basin Authority (MDBA) was established under the federal Water Act 2007 to support the sustainable and integrated management of the water resources of the Murray-Darling Basin in a way that best meets the social, economic and environmental needs of the Basin and its communities. The MDBA leads the planning and management of Basin water resources, and coordinates and maintains collaborative long-term strategic relations with other federal, state and local government agencies; industry groups; scientists and research organisations.

In late 2012, the Australian Government and the Basin States adopted a revised Basin Plan (the Plan) which sets limits on water use at environmentally sustainable levels by determining long-term average Sustainable Diversion Limits for both surface water and groundwater resources. The Plan is an adaptive framework and will be rolled out over seven years. It allows for further improvements in outcomes through a sustainable diversion limits adjustment mechanism and a constraints management strategy. The Basin Plan includes:

- an environmental watering plan to optimise environmental outcomes for the Basin;
- a water quality and salinity management plan;
- requirements that state water resource plans will need to comply with, if they are to be accredited;
- a mechanism to manage critical human water needs, and
- requirements for monitoring and evaluation the effectiveness of the implementation of the Basin Plan.

Delivering a healthy working Basin requires the integration of social, economic and environmental objectives based on the best available information and knowledge. Over the last decade the MDBA and its predecessors have made significant investments in remote sensing and related technologies in the development of the Plan, and the delivery of numerous projects and programs. However, while the benefits of remote sensing technologies have long been recognised by the MDBA, and indeed incorporated into some existing monitoring programs, the full capabilities over a range of spatial and temporal scales, within a holistic monitoring framework have not been fully embraced.

This report was commissioned to provide an independent and critical appraisal of the current and future potential of remote sensing and related capabilities to contribute to the key business and information needs of the Murray Darling Basin Authority.

The key business and information needs of the MDBA were identified through a series of internal workshops and review of internal MDBA documentation, with a focus on the primary outcomes and objectives outlined in the Basin Plan in relation to the Monitoring and Evaluation Plan (MEP), and the Compliance and Assurance Strategy (CAS). Additional requirements were also identified with regard to the needs of other MDBA programs such as The Living Murray (TLM) and the operations of River Murray Water (RMW).

The report provides a summary of 20 broad topic areas which cover the primary business and information needs of the MDBA that may be addressed by remote sensing (Chapter 3). For analysis purposes, and to allow the findings of this report to be easily aligned with broader requirements, these needs have been further aggregated according to the National Framework for the Assessment of River and Wetland Health (FARWH), with some additions where necessary.

Chapter 4 provides an overview of the current and near-term remote sensing platforms that are relevant to monitoring the Murray Darling Basin, and their capabilities in terms of spatial, temporal and spectral resolution. Knowledge of the spatial, temporal and spectral resolutions of remote sensing data is fundamental to understanding how these data sources may be used to establish baselines and detect change in a cost-effective and efficient manner.

Chapter 5 presents a set of generally accepted principles for developing environmental monitoring systems and a broad conceptual system design which provides a framework for how remote sensing and related technologies may the used to support the agencies business and information needs.

Chapter 6 provides a review and synthesis of the potential for remote sensing to contribute to the primary business and information needs of the MDBA. It draws on previous major reviews, recent published literature, existing operational programs in Australia, an Expert Workshop conducted in December 2012, and further consultation with the State jurisdictions.

Chapter 7 provides a summary of the mechanisms each Basin State has in place to ensure ongoing acquisition, management and access to high resolution remote sensing products to meet the business requirements of local, regional and state government organisations, and identifies opportunities for co-investment by the Australian Government.

Chapter 8 presents a summary of existing operational mapping and monitoring programs that utilise remote sensing to meet national, state, regional and local information needs. A number of examples are provided where remote sensing has been successfully applied to answer questions similar to those posed by the MDBA. National initiatives that align with MDBA business and spatial information needs are also outlined. There are many potential avenues for collaboration between Regional, State, and Federal Government agencies and MDBA, and these opportunities are discussed.

Finally, the report presents a number of key findings on how remote sensing and related technologies may best be utilised, and priorities for investment (Chapter 9). There is clearly significant potential for remote sensing and related technologies to play a greater role in the Murray Darling Basin Authority’s operations, and in many cases, to provide a more cost-effective, efficient and transparent means of achieving specific agencies business and information needs. Importantly, there is no single solution and remote sensing technology must be employed in the context of an overarching strategic framework that addresses internal needs and reporting requirements of the Basin Plan. Information is required at a range of spatial and temporal scales, and requires a commitment to a suite of technologies, infrastructures, methods, skills and knowledge (i.e. people) to take full advantage of available opportunities, now and into the future.

3. BUSINESS AND INFORMATION NEEDS OF THE MDBA

The key business and information needs of the MDBA were identified through a series of internal workshops and review of internal MDBA documentation, with a focus on the primary outcomes and objectives outlined in the Basin Plan in relation to the Monitoring and Evaluation Plan (MEP), and the Compliance and Assurance Strategy (CAS). Additional requirements were also identified with regard to the needs of other MDBA programs such as The Living Murray (TLM) and the operations of River Murray Water (RMW). The workshops focused on those information needs that could potentially be addressed by remote sensing, and hence the information needs identified in this report are by no means exhaustive of the total needs of the MDBA – they are necessarily focused on those needs that have the potential to be addressed using remote sensing now or in the near future.

The workshops identified 20 broad topic areas which cover the primary business and information needs of the MDBA that may be addressed by remote sensing. For analysis purposes, and to allow the findings of this report to be easily aligned with broader requirements, these needs have been further aggregated according to the National Framework for the Assessment of River and Wetland Health (FARWH), with some additions where necessary. The FARWH is a national framework that aims to provide assessments of the aggregate impacts of water resource use on rivers and wetlands in Australia. The framework has the support of both federal and state government jurisdictions; has been developed from many existing programs such as the Sustainable Rivers Audit (SRA), and covers a wide range of aspects relevant to the MDBA. It was therefore considered a good basis with which to order the information needs of the MDBA associated with remote sensing.

The FARWH acknowledges that ecological integrity is represented by all the major components of the environment that comprise an ecosystem (Norris *et al.* 2007a). The framework uses seven components to assess the health of river and wetland health (Alluvium Consulting, 2011):

- physical form,
- wetland extent,
- water quality,
- aquatic biota,
- hydrological disturbance,
- fringing zone and catchment disturbance

While the framework doesn't specifically stipulate which indices are to be used to represent each component, it does provide for the development of indices that allow for a nationally comparable assessment of river and wetland health (Norris *et al.* 2007a). These indices are structured in such a way as to enable them to be compared between themes, and be relative to a 'reference' condition, expressed as a value ranging between 0 (severely modified) to 1 (similar to reference). This approach has synergies with many of the MDBA's information needs -- i.e., many variables measured in the future will be compared against their status at the time of Basin Plan implementation.

Spatial and temporal scale is a key consideration in the management of water resources, the nature of the questions we need to answer, and how we view riverine landscapes through remote sensing. For these reasons, the identified questions were allocated to the scales at which the MDBA requires the information, and the scales that remote sensing may best provide information to answer them. Five broad spatial scales were considered:

- Individual site or reach scale;
- Asset scale (e.g., Barmah-Millewa);
- Floodplain scale;
- Valley scale, and

- Murray-Darling Basin scale.

The proposed information needs have also been placed into several temporal scales based on the temporal variability of the phenomenon being measured and the frequency at which the MDBA has to report on that phenomenon, ranging from:

- Specific events (e.g. environmental watering)
- Seasonal, and
- Annual or periodic. (e.g. 5 yearly reporting)

The following sections outline the information needs of the MDBA as they relate to remote sensing. These are grouped by the relevant components presented in the FARWH with the addition of two components - socio-economic and environmental flows that are specific to the information needs of the MDBA. Links are also made between information needs of the MDBA and some of the suggested indices that have been used under the FARWH approach. It should be noted that while the *wetland extent* and *fringing zone* components of the FARWH framework are not specifically referred to in this report, the MDBA information needs placed in other components do cover these areas. For example inundation extent was placed under the physical form component, but could have also been described under the wetland extent component. Given the inherent interactions of the components, the grouping of these needs was rather arbitrary in some cases. The spatial and temporal scales at which these needs are required to be reported are further expanded in Appendix A – Table 3.1.

Physical Form

The physical form component within FARWH assesses the local habitat and its likely ability to support aquatic life (Norris *et al.* 2007a). Testing of the framework employed the SedNet modelling of sediment accumulations as a primary index of physical form (Norris *et al.* 2007b). The information needs identified for the MDBA relating to this theme revolve around gaining an understanding of the morphology of floodplains and flow paths of the basin, to provide reliable predictions and models of inundation extent and duration throughout the river systems of the basin. This need was expressed by a range of teams within the organization as forming the basis for many of the associated information needs such as biotic response to watering, accountability and liability in delivering environmental water and ground-surface water connectivity. Information is required at a range of spatial scales, from small scale site/reach information, up to information relevant at the valley scale. Temporally, information is required over the scales of a single flow event, seasonally and on an annual basis for reporting purposes.

Water Quality

The water quality component considers the effects on biota of longer term changes in water quality, and has been measured in the FARWH using indices such as suspended sediments, total nutrient concentrations (particularly nitrogen and phosphorus), salinity and toxicant levels (Norris *et al.* 2007a). This is similar to the water quality information required by the MDBA, with the addition of variables such as pH, dissolved oxygen, and other algae based measures related to the quality of water for stock and domestic purposes. Measurement of these water quality parameters is required at the valley scale, during individual events and on a seasonal basis. A need to monitor larger scale algae and blackwater events at the floodplain and valley scale was also identified in the workshops. This was to provide timely and accurate advice to the community on the movement of these events, as well as to identify the potential source and sink areas of algae and blackwater events for future management. Salinity monitoring was also identified in the workshops as being required at the valley scale, over seasonal to annual timescales.

Aquatic Biota

The aquatic biota component of the FARWH represents the response of biota to changes in the environment (Norris *et al.* 2007a). Macroinvertebrate community structure through the AUSRIVAS model has been the most popular index used to inform the aquatic biota component, due primarily to the extent and consistency of existing monitoring data across the country. Other indices such as fish, water plants, algae, riparian vegetation and water birds have been suggested for future use when sufficient data sets become available (Norris *et al.* 2007c).The MDBA's information needs in this space revolve around two main areas; measuring past and present ecological extent and condition; and strengthening the ecological response to environmental watering under the Basin Plan and TLM programs. Vegetation was highlighted as being a major focus here at the site/reach, asset and floodplain scales, in both assessing the ecological benefits of watering, works and measures employed within the basin, and to improve the relationships within the Murray Flow Assessment Tool (MFAT) which is being used by the MDBA in its ecological benefit analysis. Information here is required over individual event and seasonal scales.

Hydrological Disturbance

The hydrological disturbance component of the FARWH deals with the changing surface and groundwater flow regimes, and how these influence biotic communities. Indices used in the FARWH revolve around modelled changes to flow regimes at the flow regime, history, pulse and flow hydraulics scales compared to pre development conditions (Norris *et al.* 2007c). The information needs of the MDBA relevant to hydrological disturbance relate to the estimation of floodplain harvesting and losses from evapotranspiration (ET), improving characterisation and understanding of surface–ground water connectivity, and monitoring groundwater use outside of currently monitored areas. Losses as a result of floodplain harvesting and ET are at present inadequately accounted for in the MDBA's hydrological models. More robust knowledge of these losses would also help in the areas of compliance and accounting of water resources in the basin. Information here is required at the site/reach, asset, floodplain and valley scales over event, seasonal and annual timescales. Improved understanding of surface-ground water connectivity would also provide more reliable estimations of recharge, underground connections and aquifer storage. Information at broader spatial scales (valley to basin) over seasonal and annual timescales is also required. Similarly, more comprehensive monitoring of groundwater use at valley and basin spatial scales over seasonal and annual timescales is required to provide more robust accounting of this resource.

Catchment Disturbance

The catchment disturbance component of the FARWH incorporates the extent and changes relating to vegetation cover, infrastructure and land use on river and wetland extent and condition, and the biota (Norris *et al.* 2007a). Indices that have been used in the framework include changes in infrastructure, Agricultural Land Cover Change (ALCC) and land use changes. These indices have all been measured using remote sensing data types (Norris *et al.* 2007c). The information needs of the MDBA align closely with these indices, being centred on changes in vegetation cover, land cover, land use and land management. In this context, assessing baseline, trends and potential changes in land cover, land use and land management are required as inputs into hydrological models, and also to assist with longer term development of water sharing plans. In addition, information on vegetation type, extent and condition is needed to inform potential changes to groundwater recharge/discharge through interception and bushfire risk. This information is predominantly needed at valley to basin spatial scales and monitored over annual timescales, noting the seasonal nature of some land use and management practices (e.g. double cropping).

Socio-Economic

Given the focus of the MDBA on balancing social, economic and environmental factors with regards to water reform in the Murray Darling Basin, many of the information needs identified were associated with assessing the socio-economic change resulting from water reform. Data pertaining to changes in cropping type over time, such as from irrigated to non-irrigated, were identified as informing a number of areas over a range of spatial and temporal scales. At the site/reach scale, data on seasonal cropping type may be related to water extraction to identify potential cases of over extraction by irrigators. More broadly, information of the valley scale changes in the distribution of cropping types is required to assess the influence of water reform and the socio-economic implications at the valley scale. Changes to the seasonal and annual patterns of cropping across the basin could influence basin communities. Hence an understanding of these changes is required for assessment and future prediction. Finally, knowledge of the distribution of water harvesting and storage structures, industries and plants is required to assist with the development of water-sharing plans and development proposals.

Environmental Flows

Environmental flows are a tool that is being used by the MDBA to protect and restore the resilience of the Basin's rivers, wetlands, floodplains, lakes and red gum forests and other assets, together with the plants and animals that depend on them. The Authority is responsible for developing a Basin wide environmental watering strategy in conjunction with state partners and holders of environmental water as well as local communities. Under the Basin Plan, the MDBA is required to develop annual watering priorities to guide environmental water management across the Basin. The annual environmental watering priorities are the watering activities identified as being the most important for the coming year. Where possible the annual priorities will identify and recommend environmental flows that address risks and threats to the health of the Basin’s rivers and wetlands.

The Environmental Watering Plan sets targets to measure progress towards its environmental objectives. Measuring ecological change is difficult; ecosystems are complex and can be affected by multiple factors. Responses to increased watering can take a long time to reveal themselves. This is even more complex on a Basin-wide scale. Ecological responses to environmental flows can also be confounded by a range of external factors such as land use, fire and seasonal variability. Consequently, measuring ecological change (or progress towards an objective) is best undertaken over a range of time frames, at a range of scales, across a suite of important ecological attributes and, where progress at the Basin scale is being measured, at a range of locations.

Efficient delivery of water to meet Basin Plan requirements is likely to include supplementing or piggy-backing stored water onto natural flow events. The ability to determine the flooding of land associated with natural flows versus managed flows is an important need for the MDBA especially in terms of liability for the flooding of private land. Improved measurement and monitoring of releases and extractions from storages and river channels is needed to ensure precise compliance and accounting of river operations. Knowledge of the antecedent catchment and floodplain conditions is also required for better prediction of flood timing and inundation extent and duration at site to valley scales and from individual events to seasonal and annual timescales.

Environmental watering must be monitored to ensure that it reaches identified assets and has the intended effects. The effectiveness of environmental watering will need to be assessed against predicted outcomes, thereby helping to improve the accuracy of future predictions. Monitoring, evaluating and reporting the effectiveness of policies and actions within an adaptive management framework are therefore essential.

4. KEY TECHNOLOGIES AND DEVELOPMENTS

An Overview of Current and Near-term Remote Sensing Capabilities and Related Developments

Addressing the broad information needs of the MDBA such as characterisation of floodplain geomorphology and hydrological regimes, and mapping the ecological response of vegetation communities to environmental flows with remote sensing requires different technological approaches and typically an integration of data sources. It is unlikely that one single sensor will ever be the optimum solution for capturing all the information needs of even one of the broad information needs. Rather, the synergistic use of optical, radar and laser scanning technologies is more likely to provide an optimum solution, particularly when calibrated/validated and integrated with appropriate field measurements.

The following section provides an overview of the current and near-term remote sensing platforms and their capabilities in terms of spatial, temporal and spectral resolution. Knowledge of the spatial, temporal and spectral resolutions of remote sensing data is fundamental to understanding how these data sources may be used to establish baselines and detect change in a cost-effective and efficient manner. The detection and characterisation of biophysical and geophysical attributes at a range of spatial and temporal scales is limited by the technological constraints of available systems. The full technical specifications of the remote sensing platforms discussed are provided in Appendix B.

Like all technology-based sectors, remote sensing platforms and associated technologies are developing at a rapid rate. It is therefore incumbent on users to regularly review these new capabilities and to plan ahead for adoption of new technologies, while also recognising that one of the most valuable qualities of remote sensing is also to provide a consistent record (archive) of changes in our landscape through time using proven technologies. To gain full value, users must not only make a long-term commitment to seeking new capabilities which provide more cost effective solutions to questions, but also to the development of consistent archives which provide a consistent and true record of landscape change.

Active and passive sensors

The majority of sensors use reflected radiation from the sun to illuminate the landscape and subsequently acquire their measurements. These sensors are termed ‘passive’, whilst those that generate their own energy, which is transmitted to, and reflected from the surface and subsequently measured, are considered ‘active’ sensors.

Passive optical sensors, including for example, Landsat MSS/TM and SPOT HRV, measure the intensity of reflected light energy (following transmission, absorption and scattering) in the visible (VIS, 400 – 700 nm), near infrared (NIR, 700 – 1300 nm) and shortwave infrared (SWIR, 1300 – 3000 nm) wavelength regions of the electromagnetic spectrum (EMS). A handful of sensors also operate in the thermal infrared (TIR, 3000 – 13000 nm) wavelength region, including Landsat MSS/TM, AVHRR and ASTER.

Active sensors operate in both the microwave (1 mm – 1 m) and optical regions, and include radio detection and ranging (Radar) sensors and light detection and ranging (LiDAR) sensors.

Radar operates as an active or passive system. Active radar including Synthetic Aperture Radar (SAR) transmit and receive pulses of polarised energy and record the time delay and intensity (backscatter) of the echoed signal. Passive radar, including radiometers, records the thermal emissivity from the ground at various frequencies.

Spatial resolution

The spatial resolution of a sensor generally refers to the size of the smallest feature that can be resolved. Typically given in units of length (e.g. metres), it depends on the instantaneous field of view (IFOV) of the observing sensor. The spatial resolution of satellite platforms is generally defined as very high (VHR, < 5 m), high (5 – 10 m), moderate (10 – 100 m) and coarse (> 100 m). Each pixel of a VHR image with a spatial resolution of, for example, 2 m displayed at full resolution will represent an area of 2 x 2 m on the ground.

The importance of spatial resolution is dependent on the spatial heterogeneity, or composition and configuration of the landscapes being mapped, and the nature of the changes being monitored (Gustafson, 1998). Ideally, the resolution of the sensor being used should be aligned with the scale of variability in the landscape. Highly fragmented landscapes where most of the remnant vegetation occurs as isolated trees or narrow riparian vegetation, requires much higher resolution imagery to map and monitor reliability than large contiguous forest areas. For example, Wood *et al.* (2006) mapped a 25 km^2 area in northern Victoria dominated by narrow riparian vegetation. Using 2.5 m resolution SPOT5 and 25m resolution Landsat produced areas of 213 ha and 19ha respectively, a tenfold difference in area.

Technology is developing rapidly, and a number of commercial satellites are now capable of acquiring VHR imagery at 0.5-2 m resolution, while airborne digital imaging systems are now typically capable of acquiring imagery at 0.05-0.5 m resolution. The spatial resolution of sensors such as airborne LiDAR are generally described in terms of the number of pulses per square metre, and the resolution of gridded products derived from the point cloud collected. Typically 1-4 pulses per square metre are collected to derive 1 m gridded products, with some applications collecting >25 pulses per square metre.

Temporal resolution

The temporal resolution of a sensor refers to the potential frequency of observations that may be collected. The importance of temporal solution is dependent on the rates of change that are occurring and factors such as seasonal variability, growing seasons and phenology, timing and duration of events. In the case of emergencies, the time between acquisition and imagery delivery may also be critical.

All satellite platforms have orbit characteristics that define their standard revisit capabilities. Some satellites (largely commercial) have tasking abilities which allow the sensor to be “pointed” at a target area from adjacent orbits, increasing the frequency of observation of that area (and forgoing observations in other areas). Landsat, for example, provides global coverage at 25 m resolution every 16 days, and MODIS offers daily global coverage at 250 m resolution. Other platforms operate constellations of the same sensor type, or with “pointing” capabilities to increase revisit frequencies. For example, the RapidEye constellation of 5 identical satellites can acquire 5 m multispectral imagery daily with viewing angles of less than 20 degrees within a 77 km swath. The Pleiades constellation of 2 satellites provides daily revisit capabilities at 0.5 m resolution, and the ability to capture up to 10 targets 15 km wide or 20,000 km2, in a single pass with viewing angles less than 20 degrees. Of course airborne platforms offer the greatest on-demand flexibility.

Long-term archives of remotely sensed data are crucial in establishing historical baselines against which to chronicle and quantify change. A key and under-valued dataset is aerial photography. Geoscience Australia and State Agencies hold archives dating back to the 1940s for many areas of Australia. The archives of Landsat and SPOT extend back to 1972 and 1986 respectively. Radar archives, which provide all weather observations, include: JERS-1 (1992 – 1998), RADARSAT-1 (1995-) and ERS-1/2 (1991-2000/1995-2011).

Spectral resolution

Spectral resolution refers to the width and number of the spectral bands of an observing sensor. Optical sensors that record radiation in a few, broad (50 – 300 nm) continuous or discontinuous spectral bandwidths are referred to as multispectral (e.g., Landsat, SPOT). Hyperspectral sensors record radiation in numerous, very narrow (10 – 20 nm) spectral bandwidths (e.g., HyMap, CASI). The high spectral resolution often assists the discrimination of different targets based on their spectral response in each of the narrow bands.

Imaging radars transmit and receive polarised energy in wavelengths ranging from 3 cm (X-band) to 100 cm (P-band). Typical SAR band allocations include P-band (Frequency range: 0.3 – 1 GHz, Wavelength range: 60 – 100 cm), L-band (1 – 2 GHz, 15 – 30 cm), S-band (2 – 4 GHz, 7.5 – 15 cm), C-band (4 – 8 GHz, 3.75 – 7.5 cm) and X-band (8 – 12 GHz, 2.5 – 3.75 cm). In general, the lower the frequency, the greater the propagation efficiency, i.e., penetration, of the radar wave through the material.

The spectral region in which observations occur largely dictates the level of information that can be extracted from remotely sensed data. For floodplain and wetland habitat mapping, data acquired in optical, thermal and microwave regions can be used. Using spectral information from different sensors, specific vegetation types for example, can be better discriminated from other surfaces using selected wavebands or derived products (e.g., ratios, texture measures). Discrimination of species is generally reliant (but not exclusively so) on the use of optical (visible to shortwave infrared) reflectance data. Data acquired by SAR have also been used to discriminate structurally diverse vegetation communities. The exclusion of a particular spectral channel may render a sensor less suitable for discriminating wetland types or surfaces.

For quantifying the three-dimensional structure and biomass of vegetation, data from sensors that penetrate the canopy and interact with underlying vegetation components (e.g., SAR and LiDAR) are required. Surface topography in the form of digital elevation models (DEMs) can be extracted from stereo aerial photographs (photogrammetry), stereo satellite images (e.g., SPOT stereogrammetry), tandem radar pairs (radar interferometry, InSAR) and LiDAR point clouds.

Optical Remote Sensing Platforms

The following sections outline available spaceborne and airborne optical sensors, decommissioned and future/proposed optical sensors (full specifications provided in Appendix B – Tables 4.1 – 4.5). Optical systems have certain advantages that warrant their inclusion in a holistic monitoring framework. System selection should be application driven and the following parameters taken into account:

- Availability of historic archives from the 1940’s – 1950’s (aerial photography) and 1970’s – 1980’s (Landsat and SPOT) for change analysis (arguably the most important benefit);
- Spatial coverage (10’s of kms – 100’s of kms – 1000’s of kms);
- Spatial resolution (very high – high – moderate – coarse);
- Spectral range (VIS – NIR – SWIR – TIR); and
- Temporal frequency (daily – weekly – fortnightly – monthly).

Aerial photography (both film and digital) is also included in the broader realm of optical remote sensing. Acquisition of true colour (visible) and colour infrared (CIR) photographs and production of orthomosaics and Digital Elevation Models (DEMs) from stereo pairs is possible.

Operational spaceborne optical sensors

Current operational satellite optical sensors and their technical specifications are summarised in Appendix B – Table 4.1. Satellite optical sensors acquiring at very high resolution (VHR, < 5 m) include IKONOS, Quickbird, Worldview-1/-2, GeoEye-1 andPleiades-1A/1B. The SPOT-5/-6, FORMOSAT-2 and RapidEye satellites acquire optical data at high spatial resolution (5 – 10 m). All the listed sensors observe in the VNIR wavelength range, with SPOT-5 additionally acquiring in the SWIR. Moderate resolution (10 – 100 m) optical sensors include the Landsat series, SPOT-4, ASTER, Hyperion and IRS-P6/Resourcesat-1/-2. Optical sensors imaging at coarse (> 100 m) resolution include MODIS and AVHRR.

Very High Resolution (VHR) optical sensors

Quickbird and IKONOS are two almost complementary multispectral satellite systems with very similar configurations. ***Quickbird***, launched in 2001 orbits at 450 km, on a potential 1 – 3.5 day repeat cycle, and acquires data in five bands (spanning 0.45 – 0.9 µm) with three VIS, one NIR and one panchromatic (PAN) band, at spatial resolutions of 2.44 – 2.88 m (MS) and 0.61 – 0.72 m (PAN). ***IKONOS*** was launched in 1999 and orbits at 680 km on a 3-day repeat cycle. IKONOS acquires data in five bands similar to Quickbird, but at coarser spatial resolution (4 m and 1 m for MS and PAN respectively).

More recently, Worldview-1 and -2 satellites were launched in 2007 and 2009 respectively. ***Worldview-1*** is a high capacity panchromatic imaging system, capable of acquiring 0.5 m resolution imagery. The satellite orbits at 496 km, and has a potential revisit time of 1.7 days. ***Worldview-2*** orbits at 770 km with a potential revisit time of 1.1 days. The satellite provides 0.5 m panchromatic and stereo optical data and multispectral data. Spectral data are acquired in eight multispectral bands (spanning 0.4 – 1.04 µm), including four standard bands (red, green, blue and NIR1) and four new bands (coastal, yellow, red edge and NIR2). Of particular interest is the red edge band which has demonstrated potential to provide information relating to chlorophyll absorption in leaves, which may assist with vegetation discrimination and health monitoring.

GeoEye-1 was launched in 2008 and acquires data in six bands (spanning 0.45 – 0.92µm), with three VIS, one NIR and one PAN band, at 0.41 m (PAN) and 1.65 m (MS) spatial resolution.

Pleiades-1A and ***-1B*** satellites were launched in 2011 and 2012 respectively, affording a swath width of 20 km and a potential repeat cycle of 1 day using both satellites. The High Resolution Imager (HiRI) on-board both satellites observes in five bands (spanning 0.44 – 0.91µm), with three VIS, one NIR band at 2m spatial resolution, and one PAN band, at a spatial resolution of 0.5 m. Pleiades satellites are highly agile, and provide some unique capabilities to “strip map” and produce mosaic images up to 100 km by 100 km areas on a single pass, as well as stereo imagery from a single pass.

High resolution optical sensors

SPOT-5 launched in 2002 comprises two High Resolution Geometry (HRG) instruments and one High Resolution Stereo (HRS) instrument. Data are collected in five spectral bands (spanning 0.5 – 1.75 µm) with two VIS, one NIR, one SWIR and one PAN band, at spatial resolutions of 10 m (VNIR-SWIR) and 5 m (PAN). The two 5 m panchromatic sensors are offset by half a pixel to produce a 2.5 m product. ***SPOT-6*** launched in 2012 acquires spectral data in five bands (spanning 0.45 – 0.89 µm) with three VIS, one NIR and one PAN band, at 8 m (MS) and 1.5 m (PAN) spatial resolutions respectively. **SPOT-7** is proposed for launch in 2014. They form a constellation of satellites designed to provide continuity of high resolution, wide-swath data up to 2023. The SPOT series operate on a standard 26 day repeat cycle, and with tasking repeat cycles over specific areas can be reduced to 2-3 days.

FORMOSAT-2was launched in 2004 and acquires spectral data in five bands (spanning 0.45 – 0.9 µm), with three VIS, one NIR and one PAN band, at spatial resolutions of 2 m (PAN) and 8 m (MS).

RapidEye observes in five spectral bands (spanning 0.4 – 0.85 µm, VNIR), at 6.5 m spatial resolution with a 77 km swath. RapidEye operates a unique constellation of 5 identical, calibrated satellites. Using all 5 satellites provides daily revisit capabilities that can acquire up to 4 million km^2 per day. As with WorldView-2, the red band offers additional opportunities for vegetation discrimination. The combination of 5 satellites offers significant opportunities to track the progression of floods over large areas.

The ***ZY-3*** satellite launched on 9th January 2012 is the first civilian high-resolution stereo mapping satellite of China. It is an optical satellite using three line-array CCD in push-broom imaging mode. It is equipped with three panchromatic cameras respectively positioned at nadir, forward and backward positions, and one multispectral camera. The panchromatic sensor with 2.1 m ground sample distance (GSD) at nadir and panchromatic sensors with 3.6 m GSD at forward and backward provide high resolution, stereo imagery. The multispectral sensor collects blue, green, red, near infrared bands with 5.8 m nadir resolution, providing natural-colour imagery for visual interpretation and colour-infrared imagery for remote sensing applications. The satellite can collect 6 to 8,150,000 km^2 image strips per day (about 1.8 TB), 3 to 4 of which are in China and 3 to 4 of which are distributed overseas. ZY-3 has a potential revisit cycle of 5 days over a 51km swath with priority programming.

Moderate resolution optical sensors

The ***Landsat series*** has been operational since 1972, with ongoing continuity of data collection ensured with the recent launch of Landsat-8 (February, 2013). Currently operational satellites include Landsat-7 and the recently launched Landsat-8. An advanced ***Landsat-7*** was launched in 1999 with the Enhanced Thematic Mapper (ETM+) on board, which imaged in eight spectral bands (spanning VNIR-SWIR-TIR, 0.45 – 23.5 µm, and including a PAN band, 0.52 – 0.9 µm). Spatial resolutions of 30 m (VNIR), 15 m (PAN) and 60 m (TIR) were achieved, over a 150 km swath. Hardware failure, specifically the loss of the scan line corrector (SLC) in May 2003, resulted in gaps in the data record and missing data. The successful launch of ***Landsat-8***, the Landsat Data Continuity Mission (LDCM), in February 2013 was therefore quite timely. LDCM incorporates the Operational Land Imager (OLI) with spectral data acquired in nine bands (spanning the VNIR-SWIR-TIR and PAN, 0.43 – 12.5 µm) at spatial resolutions of 15 m (PAN), 30 m (MS) and 100 m (TIR). NASA has an open data policy with regard to data supply, and Landsat data are available for free online download through the US Geological Survey (USGS) and other distributors, including Geoscience Australia.

SPOT-4 was launched in 1998 and acquires spectral data in five bands (spanning the VNIR-SWIR, 0.5 – 1.75 µm and including a PAN band, 0.61 – 0.68 µm) at 20 m (MS) and 10 m (PAN) spatial resolution. The satellite has a revisit time of 26 days and data are collected over a 60 km swath.

ASTER, the Advanced Spaceborne Thermal Emission and Reflection Radiometer, on board NASA's Terra satellite was launched in 1999. Spectral data is acquired in fourteen bands (spanning the VNIR-SWIR-TIR, 0.51 – 11.65 µm) at 15 m (VNIR), 30 m (SWIR) and 90 m (TIR) spatial resolutions. The satellite has a revisit time of 16 days.

The ***Hyperion*** imaging spectrometer is on board NASA's EO-1 satellite, launched in 2000. The satellite has a repeat visit time of 16 days. Spectral data is acquired in 198 bands (spanning the VNIR-SWIR, 0.43 – 2.5 µm) at 30 m spatial resolution, and over a 7.65 km swath.

IRS-P6 (Resourcesat-1) and IRS-P7 (Resourcesat-2) are the Indian Remote Sensing Satellites, launched in 2003 and 2011 respectively. On-board both Resourcesat-1/-2 are the Linear Imaging Self Scanner (LISS) III and IV and the Advanced Wide Field Sensor (AWIF). The LISS-III collects spectral data in four bands (spanning the VNIR-SWIR, 0.52 – 1.75 µm) at 23.5 m spatial resolution and over a 141 km swath. The LISS-IV collects spectral data in the VNIR range at 5.8 m spatial resolution and over a 70 km swath. AWIFS acquires data across the VNIR-SWIR range at 55 m spatial resolution and over a 740 km swath. Satellite revisit times are 5 days for Resourcesat-1 and 26 days for Resourcesat-2.

DMC-2G, the Disaster Monitoring Constellation – Second Generation, is an international program of five low earth orbiting microsatellites that provide daily global coverage at moderate resolution (22 – 32 m) in three spectral bands for rapid response disaster monitoring and natural resource management applications. The multispectral sensors operate in the VNIR wavelengths (0.63 – 0.9 µm) at 22 – 32 m spatial resolution and over a 650 km swath. One of the satellites in the constellation, Nigeriasat-2, operates in multispectral mode but includes a higher resolution option (2.5 m panchromatic and 5 m multispectral).

Coarse resolution optical sensors

MODIS was on board both NASA's Terra and Aqua satellites, launched in 1999 and 2002 respectively. MODIS acquires coarse resolution (250 – 1000 m) spectral data in 2 – 36 bands (spanning the VNIR-TIR, 0.4 – 14.5 μm) and over a 2330 km swath. Data is free for download, and the following link provides access information: http://modis.gsfc.nasa.gov/data/. ***AVHRR*** was launched in 2009 and acquires spectral data in six bands (spanning VNIR-SWIR-TIR, 0.58 – 12.5 μm) at 1100 m spatial resolution and over a 3000 km swath.

Operational airborne optical sensors

Multispectral and hyperspectral scanners

Airborne sensors, whilst providing very high spatial (typically < 5 m) and spectral (3 – 20 nm) resolution data are hampered by limited aerial coverage and high acquisition costs, particularly if repeat coverage is required. Specific areas can be targeted for image acquisition during optimal weather windows. The flying height of the aircraft and field of view (FOV) of the instrument determine the spatial resolution. The specifications of a few commonly used airborne hyperspectral and multispectral systems are outlined in Appendix B – Table 4.2.

Commercially available hyperspectral sensors are limited to a handful of airborne systems, including HyMap and CASI. The ***HyMap***, owned and operated by HyVista Corporation, can be flown on a twin-engine, unpressurised aircraft, operational at altitudes ranging between 1.5 and 4.5 km. The sensor acquires spectral data in 128 bands (spanning 0.45 – 2.5 μm), comprising 4 main modules with 32 spectral channels in each: the VIS (0.45 – 0.89 μm), NIR (0.89 – 1.35 μm), SWIR1 (1.4 – 1.8 μm) and SWIR2 (1.95 – 2.48 μm). The FOV varies from 30 – 65° with a resulting swath of 2.3 – 4.6 km in the across-track direction. Spatial resolution is dependent on the flying height. The high signal to noise ratio (SNR, 500:1 – 1000:1) of HyMap ensures high signal clarity and information content.

The ***CASI*** is operated by ITRES, Canada. The CASI-1500 is a VNIR sensor (spanning 0.38 – 1.05 μm) with a relatively large 1500 pixel FOV (40° across-track), providing coverage over a 3.8 – 22.5 km swath. The system can be programmed to acquire up to 288 spectral bands to suit a wide range of applications. High spatial (0.25 – 1.5 m) and spectral resolutions (< 3.5 nm) and high SNR ensure high quality hyperspectral data from an airborne platform.

DMSI, ***Daedalus*** and ***DAIS*** offer high resolution, targeted multispectral coverage. The DMSI acquire spectral data in four bands across the VNIR range. Daedalus acquires spectral data in 11 bands, including eight VNIR, two SWIR and one TIR. DAIS acquires 79 bands including six TIR bands.

Airborne digital cameras and scanners

Over the last decade, film-based cameras have effectively been phased out of operation, and airborne digital cameras and scanners now form the basis of a rapidly advancing global airborne remote sensing industry. Appendix B – Table 4.3 provides detailed specifications of the common, commercially operating metric quality sensors. Leica Geosystems airborne digital scanners, including the ADS40 and ADS80, provide accurately co-registered colour and panchromatic imagery for stereo viewing. The ***ADS40*** acquires panchromatic (0.47 – 0.68 μm) and VNIR imagery (0.61 – 0.89 μm) over a 2.5 km swath, at spatial resolutions of 0.1 – 0.5 m (http://www.digitalaerial.com/digitalimageryads40.html). The ***ADS80*** acquires panchromatic and VNIR imagery across a similar spectral range, with a FOV of 64° across-track, providing coverage over a 12 km swath. Imagery can be captured at spatial resolutions approaching 5 cm. (http://www.leica-geosystems.com/en/Leica-ADS80-Airborne-Digital-Sensor_57627.htm).

The ***DMC II$_{230}$*** is a large format digital aerial camera, developed by ZI Imaging. The system comprises five nadir-looking camera heads, with four multispectral cameras (red, green, blue and NIR) and one PAN camera. The DMC II_{230} has a FOV of 52° across-track, and is typically capable of acquiring spectral data at resolutions of up to 0.1 m. (http://www.ziimaging.com/media/ZI_DMC230_DS_en.pdf).

The Microsoft ***Ultracam Osprey*** digital camera system comprises a high performance photogrammetric nadir camera with oblique imaging capability Panchromatic and colour imagery (VNIR) are acquired at spatial resolutions approaching 0.1 m. The camera has a FOV of 69° across-track providing coverage over a 12 km swath. (http://www.microsoft.com/ultracam/en-us/default.aspx).

The VisionMap ***A3*** digital camera provides high resolution vertical and oblique imagery with a wide FOV up to 106° across-track (60,000 pixels); the A3 provides the largest footprint of available commercial aerial cameras. Colour imagery (VIS, 0.42 – 0.74 µm) is acquired at spatial resolutions of less than 0.3 m over a 1 – 23 km swath. (http://www.visionmap.com/en/products/a3-overview/a3-digital-camera).

Archive optical sensor data

Archival optical data are available through a number of decommissioned satellite programs (Appendix B – Table 4.4). In particular, the Landsat and SPOT series of satellites has been operational since the 1970's and 1980's and an extensive archive is available for investigating changes in vegetation cover and land use. ***Landsat 1-5*** carried the Multispectral Scanner (MSS), acquiring data in five spectral bands (spanning the VNIR-SWIR-TIR, 0.5 – 12. 6 µm) at spatial resolutions of 70 – 82 m (VNIR-SWIR) and 237 m (TIR) respectively. Landsat-4 and -5 also carried the Thematic Mapper (TM), collecting spectral data in seven bands (spanning the VNIR-SWIR-TIR, 0.45 – 23.5 µm) at spatial resolutions of 30 m (VNIR-SWIR) and 60 m (TIR) respectively. Landsat-5 was decommissioned in January, 2013, due to aging electronic equipment and transmitter failure. ***SPOTs 1-3***have acquired spectral data in four bands (PAN-VNIR, 0.5 – 0.73 µm) at 20 m spatial resolution since the mid 1980's.

CHRIS, the Compact High Resolution Imaging Spectrometer, was on board ESA's Proba satellite that operated between 2001 and 2012. Multi-angular spectral data was acquired in 19 – 63 programmable bands (spanning VNIR, 0.42 – 1.05 µm) at spatial resolutions of 18 – 36 m for a range of terrestrial and marine applications.

The ***CBERS*** program was initiated in the late 1990's and early satellites comprised a number of sensors including a CCD camera, Infrared Multispectral Scanner (IR MSS) and a VNIR Wide Field Imager (WFI). The IR MSS acquired spectral data across the VNIR-SWIR-TIR range at spatial resolutions of 78 m (MS) and 156 m (TIR) respectively. CBERS satellites had a 26 day repeat visit time.

MERIS, the Medium Resolution Imaging Spectrometer, was on board the ENVISAT satellite that ceased operations in 2012. MERIS acquired spectral data in 15 bands (spanning the VNIR, 0.39 – 1.04µm) at coarse spatial resolution (300 m and 1200 m for land and ocean applications respectively). MERIS had a 3 day revisit time.

Future/proposed spaceborne optical sensors

A number of proposed satellite optical sensors will ensure continuity of data collection and new scientific missions (Appendix B – Table 4.5). ***GeoEye-2*** and ***Worldview-3*** will continue to provide VHR optical data at improved spatial and spectral resolutions (in the case of Worldview) compared to their predecessors. SPOT data collection is ensured with the proposed launch of ***SPOT-7*** in 2014. The CBERS program will continue with the launch of ***CBERS-3*** in 2013. The German Space Agency (DLR) plans to launch ***EnMAP***, a moderate (30 m) spatial resolution full spectrum sensor with 200 bands (VNIR-SWIR, 0.42 – 2.45 µm); a 30° pointing range and 3-day revisit time. Whilst the spatial resolution is relatively low, the high SNR will be comparable to airborne sensors like HyMap, and cover the full spectral range applicable to vegetation and ecological process studies.

The geostationary satellite, ***Himawari-8*** is scheduled for launch by the Japanese Meteorological Agency in late 2014. The sun-synchronous satellite offers greatly improved sampling frequency of 15 minutes, raising the prospect of near-real-time monitoring of surface water, at the expense of relatively coarse resolution (1km). The Himawari-8 satellite will be (near) identical to the U.S. GOES-R satellite planned for launch in 2015.

The GMES ***Sentinel-2*** earth observation mission developed by ESA is planned for launch in 2014, and will provide continuity to services relying on multi-spectral high-resolution optical observations. Sentinel-2 will carry an optical payload with visible, near infrared and shortwave infrared sensors comprising 13 spectral bands: 4 bands at 10 m, 6 bands at 20 m and 3 bands at 60 m spatial resolution (the latter is dedicated to atmospheric corrections and cloud screening), with a swath width of 290 km. The mission orbits at an altitude of approximately 800 km and, with the pair of satellites in operation, has a revisit time of five days at the equator (under cloud-free conditions) and 2–3 days at mid-latitudes. The ***Sentinel-3*** mission, also planned for launch in 2014, is based on previous SAR technology (ERS-2 and ENVISAT), but includes an Ocean and Land Colour Instrument (OLCI). The OLCI comprises 21 spectral bands over the visible to near infrared wavelengths (0.4 - 1.02 µm) at 300 m spatial resolution, with a swath width of 1270 km. The operational configuration comprises two satellites, orbiting at around 814 km, providing a 2 day revisit capability for OLCI at the equator. The OLCI sensor on board Sentinel-3 will support applications development in water quality and pollution monitoring and land based services.

Radar Remote Sensing Platforms

This section describes operational satellite radars, radiometers and scatterometers used for soil moisture estimation, airborne SARs, previous and proposed satellite radar missions. Full specifications are provided in Appendix B – Tables 4.6 – 4.11. Unlike optical remote sensing systems, active radar systems provide their own source of illumination, and can therefore operate day and night. In addition, radar has an all-weather data acquisition capability, with cloud, fog, rainfall, aerosols and smoke all transparent to the majority of radar frequencies. Radar signals are sensitive to the (i) physical and geometric properties of surface features such as roughness, slope and orientation of objects relative to the radar beam direction, (ii) dielectric properties which depend strongly on water content (i.e., soil moisture, green vegetation biomass), and to a lesser extent (iii) density and conductivity of soil and rock materials.

Data acquired by SAR can be considered complementary to optical remote sensing. The synergistic use of radar backscatter and optical reflectance data has the potential to provide another level of detail and understanding of surface features and environmental processes.

The primary sensor parameters that determine the backscatter response are incidence angle, wavelength and polarisation. The incidence angle describes the angle between the radar illumination and the ground surface and is calculated based on near range (closest to nadir) and far range (furthest from nadir) assuming a flat topography. The incidence angle across a radar image will vary depending on the height of the aircraft or satellite. Wavelength describes the distance between crests of a sinusoidal wave. Radar wavelengths vary from centimetres to metres with shorter wavelengths being more common for imaging earth surface features. Polarisation refers to the direction of the electric field of the wave being transmitted or received by a radar antenna. Waves can be propagated and returned either vertically or horizontally. Interaction with features on the ground may cause the propagated wave to be depolarised, i.e., return some portion of the wave in a different polarisation to that transmitted. Fully Polarimetric radar systems record both the amplitude and the phase angle of the co-polarised (HH or VV) and cross-polarised (VH or HV) returns coming from a surface. Non-polarimetric radars transmit and record only single polarisation returns. Single polarised systems only record the amplitude (strength) of the return signal.

Increasingly radar data are becoming available in full polarimetric and interferometric modes. Polarimetric data are sensitive to the structure and spatial arrangement of surface and vegetation features. Radar scattering properties can be used to retrieve geophysical and biophysical parameters such as soil dielectric constant, surface roughness and slope, as well as forest height and biomass. Interferometric radar (InSAR) is valuable for DEM generation, forest height estimation and the geophysical monitoring of natural hazards. Data acquisition occurs in single-pass (simultaneous acquisition of two images over same area) and repeat-pass (repeat acquisition of same area on two different dates) modes. Differential Interferometry (DInSAR) can be used to identify sub-centimetre ground deformations due to earthquakes and detect ground subsidence over underground mine sites. A recent development is the monitoring with multiple passes over a 1 – 2 year period of the vertical change of permanent (or persistent) scatterers (PSInSAR) to measure with millimetre accuracy ground subsidence due to, for example, the extraction of groundwater from aquifers and coal seam gas extraction. Polarimetric Interferometry (Pol-InSAR) combines the advantages of both SAR polarimetry and interferometry to measure the height and depth of features, e.g., a vegetation canopy, for biomass estimation, and other applications in topographic modelling, hidden target and coherent change detection.

Operational Satellite SARs

Despite the recent losses of ALOS PALSAR and ENVISAT SAR sensors, SAR systems are on the increase, and new missions will mean that SAR data are more widely available. The characteristics of some operational SAR's are summarised in Appendix B – Table 4.6. Data acquired by SAR has demonstrated potential in land cover/land use mapping, forest biomass assessment, terrain analysis, inundation mapping and hydrological modelling.

The German Space Agency (DLR) launched ***TerraSAR-X*** in 2007 for scientific and commercial use. TerraSAR-X is a multi-modal steerable X-band radar, capable of acquiring VHR (< 5 m) data over narrow to coarse swaths. The satellite is in a near-polar orbit at an altitude of 514 km and has a revisit time of 11 days. As a follow-on and extension to TerraSAR-X, DLR launched ***TanDEM-X*** in 2010. Both systems have near identical capability, and when flown together in close formation, provide interferometric (InSAR) imaging for global DEM generation.

The Italian Space Agency (ASI) operates the ***Cosmo-SkyMed*** dual-use X-band SAR constellation. There are seven satellites in the constellation (four SAR and three optical), launched successively between 2007 and 2009. The constellation features daily revisit times and rapid access to data for disaster monitoring and intelligence gathering applications. X-band data can be acquired in selectable single and dual polarisation modes at resolutions ranging from very high (1 m) to coarse (100 m).

The Canadian Space Agency (CSA) operates the RADARSAT-1 and -2 satellites. ***RADARSAT-1*** has been operational since 1995, far exceeding its nominal 5-year design life. The system is multi-modal, with seven selectable imaging modes acquiring data at high to moderate spatial resolution, for a range of viewing angles and over narrow to extended swaths. The satellite has a revisit time of 24 days. ***RADARSAT-2*** was launched in 2007 to ensure that supply and distribution of C-band SAR data and products would meet present and future needs. RADARSAT-2 provides improved capabilities in multi-modal imaging and left- or right-looking modes.

The application of radar has demonstrated potential to inform on the spatial and temporal variation in soil moisture content at local to global scales. Full technical specifications of available satellite radars that have been used for, among other applications, soil moisture mapping are provided in Appendix B – Table 4.7.

Passive radiometers are often adopted due to high sensitivity to near surface soil moisture content, direct correlation with soil dielectric constant and minimal interference of vegetation and surface roughness. Soil moisture can also be estimated using active microwave sensors (listed in Table 4.6) that measure radar backscatter from soil surfaces. Forward scattering models are used to invert the backscatter to estimate the dielectric constant, and convert the latter into estimates of soil moisture. A combination of multi-frequency, dual or quadripolar, and multi-temporal measurements is required. The increasing number of SAR satellites and higher spatial resolution, together with shorter revisit times offers greater opportunities to improve the quality with which surface soil moisture can be retrieved from radar data (Baghdadi *et al*., 2008).

Active sensors observe at much finer spatial resolutions than passive systems, but exhibit greater sensitivity to surface roughness, topography and vegetation effects. The choice of system will be guided by the intended application. Passive data provide useful input to climate and meteorological models with low spatial resolution requirements. Active radar provides finer resolution data suitable for detailed hydrological modelling.

The ***Tropical Rainfall Measuring Mission (TRMM)*** was a joint mission between NASA (USA) and NASDA (Japan), which has been operational since 1997. TRMM’s main objective was to measure precipitation and energy exchanges from tropical and subtropical areas (Lee and Anagnostou, 2004), but data collected have also contributed to land surface monitoring and soil moisture estimation. TRMM was the first spaceborne sensor to provide soil moisture measurements over extensive areas and over a long timeframe (Bindlish *et al.,* 2003).

TRMM was launched into a 350 km sun-synchronous circular orbit with a 35° inclination angle, providing a swath width of 758.5 km. The three primary instruments on-board TRMM include the TRMM Microwave Imager (TMI), Precipitation Radar (PR) and the Visible and Infrared Radiometer System (VIRS). The TMI is a nine channel passive microwave radiometer, operating at five different frequencies (10.65, 19.4, 21.3, 37.0, and 85.5 GHz), at a spatial resolution of 50 km (at 10.65 GHz). TRMM is still collecting data but fuel for maintaining operations will likely run out in 2014. Its successor, the Global Precipitation Measurement (GPM) mission is scheduled for launch in 2014.

In 2009, ESA launched the ***Soil Moisture and Ocean Salinity (SMOS)*** satellite, a world-first, dedicated global soil moisture mapping mission (Wu *et al.,* 2011). SMOS was designed to measure two important variables, namely soil moisture and soil salinity, for use in climate and hydrological modelling and forecasting (Peichl *et al.,* 2007). The satellite was launched into a sun-synchronous orbit at an altitude of 756 km and inclination angle of 32.5°, and has a revisit time of 3 days. The passive radiometer operates at L-band (1.413 GHz), H and V polarisation, with a spatial resolution of 35 – 50 km and 0 – 50° incidence angle range.

The ***Advanced SCATterometer (ASCAT)*** on-board Metop-A, Europe’s first operational polar-orbiting satellite began operations in 2006. Since December 2008, the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) has been disseminating global 25 km ASCAT surface soil moisture data in near real-time. The ASCAT soil moisture product can be used for Numerical Weather Prediction (NWP), flood forecasting and other time-critical applications.

The ***Global Change Observation Mission (GCOM)*** or ‘Shizuku’, launched in 2012 by JAXA, provides continuity to the previous AMSR-E mission which ended operations in October, 2011. GCOM consists of two satellites, GCOM-W which carries the AMSR2 (Advanced Microwave Scanning Radiometer 2) instrument for observation of water related targets, and GCOM-C for surface and atmospheric measurements. AMSR2 operates at six frequencies between 7 and 89 GHz, over a 1450 km swath width, and will provide highly accurate measurements of microwave emission every 2 days (http://www.jaxa.jp/projects/sat/gcom_w/index_e.html).

Operational Airborne SARs

Airborne SARs operate at various frequencies and most current systems are fully polarimetric (Appendix B – Table 4.8). A major limitation of airborne SAR however, is that multi-date imagery is not easily obtainable due to the logistics and costs involved in acquiring repetitive coverage over the same area.

Intermap's ***STAR3i*** system comprises a dual antenna interferometric SAR (IFSAR) operating at X-band HH polarisation. Data collected can be processed into an orthorectified radar image (ORRI) and a digital terrain and elevation model (DTM/DEM). DEMs are nominally acquired with ±1 m RMSE vertical accuracy and 5 m spatial resolution over a 10 km swath. The ORRIs have a spatial resolution of 1.25 m and horizontal accuracy of 1.25 m. Intermap provides commercial airborne data acquisition and geospatial processing services.

PLIS, the Polarimetric L-band Imaging SAR, is a fully polarimetric airborne interferometric SAR, operating at altitudes of 300 to 3000 m, and imaging at a frequency of 1.26 GHz and in H or V polarisation modes. The incidence angle ranges from 15° from nadir on the near side of the swath to 45° on the far side. PLIS was designed to support algorithm development for soil moisture retrieval using NASA's proposed SMAP system.

NASA JPL designed the ***UAVSAR***, the uninhabited aerial vehicle SAR. UAVSAR is flown on a Gulfstream-III jet at altitudes up to 14 km. UAVSAR collects Polarimetric (PolSAR) and interferometric (repeat-pass InSAR) data that highlight different ground features and measures change in them over time. The UAVSAR has been deployed in many locations worldwide for scientific application.

The ***INGARA*** airborne X- and L-band SAR is operated by the Australian Defence Science and Technology Organisation (DSTO). The system is fully polarimetric capable of operating in stripmap, spotlight and interferometric modes. In stripmap mode, 12 – 48 km swaths may be acquired at 2 – 8 m spatial resolution. The spotlight mode affords higher spatial resolutions (0.3 m in slant range). Cross-track interferometry is achieved using repeat-pass acquisitions, and data acquired in this mode have been used for coherent change detection analysis.

GeoSAR is an airborne, dual-sided, dual-frequency (X- and P-bands) interferometric SAR system, owned and operated by Fugro EarthData. The sensor is integrated on a Gulfstream jet, capable of acquiring data from 13 km above ground level at airspeed of over 400 knots, facilitating a very fast data collection rate. The data are well suited to the generation of highly accurate DTM/DEMs, ORRIs and Topographic Line Maps (TLMs), and have demonstrated application in determining cultural, geologic and vegetative structures and land use mapping (Jenkins *et al.,* 2010). Fugro EarthData has been commercially operating the GeoSAR since 2002.

Archive SAR data

Archive SAR data are available from the 1990's for many areas worldwide (Appendix B – Table 4.9). C-band data were acquired by the ***ERS-1*** and ***ERS-2*** satellites for over a decade from 1991 and 1995 respectively. ***ENVISAT ASAR*** was operational until quite recently, decommissioned early in 2012. L-band ***JERS-1*** data are available between 1992 and 1998, and ***ALOS PALSAR*** from 2006 to 2011. Multi-frequency SAR data are available from the SIR-C/X-SAR mission in 1994, and near-global DEM data are available from the SRTM.

Future/proposed satellite SARs

Numerous agencies worldwide are committed to future launches for continuity of operational applications and exploration of new imaging technologies, including wide surveillance modes and extending interferometric applications. Continuity C- and X-band missions and a second L-band PALSAR system are scheduled, and both S- and P-band systems have been proposed. Technical specifications for future/proposed satellite SARs and soil moisture missions are presented in Appendix B – Tables 4.10 and 4.11 respectively.

Continuing access to X-band SAR data seems ensured, with the proposed Cosmo-SkyMed Second Generation (CSG-1, -2) and TerraSAR-X2 systems. The ***CSG-1*** and ***CSG-2*** satellites have proposed launch dates of 2015 and 2016 respectively, and will provide continuation from the existing four satellite Cosmo-SkyMed constellation. DLR has indicated a commercial follow-on to the existing TerraSAR-X mission, with the proposed launch of ***TerraSAR-X2*** in 2015.

Ongoing access to C-band SAR data seems ensured with the proposed ESA Sentinel and CSA RADARSAT Constellation Mission (RCM) programs. The ***Sentinel*** mission comprises two C-band satellites, with a third under consideration, and anticipated launch dates of 2013 (1A), 2015 (1B) and 2019 (1C). Given ESA's open data policy, free access to C-band data should continue. Hornacek *et al. (*2012) has suggested that the ***Sentinel-1*** system could be used to provide an operational service to derive 1 km soil moisture data using change detection algorithms developed and demonstrated with previous ENVISAT ASAR Global Monitoring mode. There is also the opportunity to provide surface water maps at 30m resolution once every 12 days globally. The ***RCM*** comprises three satellites with probable launch dates of 2014 (C1 and C2) and 2015 (C3) and expected lifetimes of seven years. Following on from RADARSAT-2, data will be acquired in multiple imaging modes at low to high spatial resolution to suit a diversity of applications.

SSTL in the United Kingdom have developed an S-band system ***NovaSAR-S*** for launch in 2013. It can be launched into either a sun-synchronous or low inclination equatorial orbit. NovaSAR-S provides moderate resolution data (6 – 30 m), suitable for a range of natural resource and disaster management applications.

Regarding L-band continuation, JAXA have approved ***ALOS PALSAR-2*** for launch in 2013. However the data access policy has not yet been determined. CONAE, Argentina, and ASI, Italy, have also proposed the launch of a fully polarimetric L-band SAR constellation called ***SAOCOM*** in 2014. It is anticipated that observations from SAOCOM will contribute to agricultural, hydrological and health applications, natural resource management and disaster monitoring and management. DLR and NASA JPL are also considering a ***TanDEM-L*** satellite as a complement to their current X-band constellation. There is also potential for the supply of P-band SAR data through ESA's ***BIOMASS*** initiative.

Future/proposed satellite radars of relevance to soil moisture estimation include SMAP and GPM. The ***Soil Moisture Active Passive (SMAP)*** mission under development by NASA JPL is anticipated to contribute to global measurement of soil moisture and freeze/thaw state for improved understanding of water, energy and carbon cycles, and application in climate modelling, flood prediction and drought monitoring. The SMAP instrument comprises both an L-band radar and L-band radiometer. SMAP algorithm development is ongoing and intends to provide estimates of near surface (top 5 cm) soil moisture with an error no greater than 0.04 cm^3/cm^3 at 10 km spatial resolution, and at 3-day intervals over the global land area.

The ***Global Precipitation Measurement (GPM)*** mission under development by NASA and JAXA will extend on the operations of the TRMM which will likely cease operations in 2014. The GPM mission will contribute to improved understanding of earth's water and energy cycles, better agricultural crop forecasting and monitoring of freshwater resources and improved forecasting of extreme events (http://www.nasa.gov/mission_pages/GPM/overview/index.html). GPM will comprise a dual frequency precipitation radar (DPR) and a passive microwave radiometer (Kubota *et al.,* 2010).

LIght Detection and Ranging Systems (LIDAR) or Laser Scanning Systems

Satellite Laser Systems

There are currently no operational satellite lasers in orbit. NASA's ***ICESat*** (Ice, Cloud and land Elevation satellite) provided multi-year elevation data between 2003 and 2009, primarily for measuring ice sheet mass balance, cloud and aerosol heights, but data also proved useful for mapping surface topography and vegetation characteristics. The GLAS (Geoscience and Laser Altimeter System; http://glas.gsfc.nasa.gov/) on board ICESat was the first LiDAR for continuous global earth observation. GLAS transmitted short pulses of infrared (1064 nm) and visible green (532 nm) light. Laser pulses transmitted 40 times/second illuminated patches (footprints) of 70 m in diameter, spaced at 170 m intervals on the earth's surface. ***ICESat-2*** is the 2nd generation orbiting laser altimeter scheduled for launch in 2016. The new system will use a micro-pulse multi-beam approach for dense cross-track sampling, and have a high pulse repetition rate for dense along-track sampling (~70 cm).

Operational Airborne LiDAR Systems

Airborne Laser Scanners (ALS), or Light Detection and Ranging (LiDAR) sensors, which are typically integrated on light aircraft or helicopters, transmit and receive their own energy source in the form of a NIR pulse which is directed downwards. The transmitted pulse reflects from objects, including tree canopies, power lines and the ground surface, and the return pulse ("point cloud") is received by the sensor. As the NIR pulse travels at the speed of light, the time-delay between pulse transmission and receipt is related directly to distance and hence to the height of objects. LiDAR also records the intensity, or magnitude of the return pulse, which is useful for interpreting and classifying the point clouds. With real time GPS and internal navigation systems (INS) that compensate for aircraft pitch, yaw and roll, most systems are capable of achieving absolute accuracies of < 1 m in the horizontal direction (x, y position), and 10 – 20 cm in the vertical direction (elevation).

Data acquired by LiDAR forms a point cloud that can be classified into ground and non-ground points using established algorithms. It is from the point cloud that DTMs representing the height of the ground surface and DEMs representing the height of the ground and surface objects such as vegetation and buildings are generated. It is also possible to analyse and quantify the three-dimensional structure and biomass of vegetation. Data acquired by LiDAR is invaluable for detailed ground surface mapping and defining subtle drainage features, although reliable height estimation in densely vegetated areas can be problematic and difficulties may be encountered in defining the precise position of channel banks.

LiDARs are characterised as discrete or full-waveform systems. Discrete systems collect 1 – 4 reflections per transmitted pulse, while full-waveform systems collect the entire return waveform at very high sampling frequencies and can record up to 80 samples per transmitted pulse. Full-waveform sensors record significantly more data per pulse, and so are potentially more useful for 3D reconstruction of objects (e.g., forest canopy structure) and estimating surface roughness and slope. Airborne LiDARs typically acquire data using small footprints <1 m in diameter. The technical specifications of a range of widely used LiDARs are provided in Appendix B – Table 4.12.

Optech have a range of airborne laser terrain mappers (ALTM; http://www.optech.ca/prodaltm.htm) to suit wide area mapping (Pegasus HA500, Orion H300), engineering grade surveys (Orion M300), and corridor mapping (Orion C300) applications. The ***Orion ALTMs*** are ultra-compact, full-waveform sensors with a 300 KHz sampling capability, very narrow pulse widths for precision measurement, fully programmable FOV and intensity capture with large dynamic range. The H300 is a high altitude sensor, operating at altitudes up to 4 km. The M300 is a mid-altitude sensor, capable of acquiring data at altitudes of 2.5 km. The C300 is a low altitude system, operating at altitudes of less than 1 km, capable of high density point collection for maximum object detail. The Orion ALTMs collect up to four range measurements (including 1st, 2nd, 3rd and last returns), and up to 4 intensity returns for each pulse, with a pulse repetition rate (PRR) of up to 300

KHz, and with a scan frequency of up to 90 Hz. The ***Pegasus*** is a multi-channel, full-waveform laser scanner, capable of high density point measurement. The sensor operates at altitudes of up to 5 km, with a wide FOV (75°). Up to four range measurements and 4 intensity returns for each pulse are collected with a PRR of up to 500 KHz and scan frequency of up to 140 Hz.

Riegl produce a variety of high performance, lightweight and compact laser scanners (http://www.riegl.com/nc/products/airborne-scanning/). The***LMS-Q780*** is a long-range, full-waveform LiDAR for wide-area mapping. The sensor has a wide FOV of 60°, PRR of up to 400 KHz, and collects data with average point density of 13 points/m^2. The ***LMS-Q680i*** is an extra-long range, full-waveform LiDAR with multiple target capability. The sensor has a wide FOV of 60°, PRR of up to 400 KHz, and collects 1st return data at a scan speed of up to 200 lines per second. The ***VQ-480i*** is a full-waveform, high-speed, compact laser scanner, capable of acquiring 10-150 lines per second. The sensor has a FOV of 60° and PRR of 50-550 KHz.

Leica Geosystems have a range of airborne laser scanners for wide-area to narrow/corridor mapping applications (http://www.leica-geosystems.com/en/Airborne-LIDAR_86814.htm). The ***ALS70*** series comprises the CM sensor for city and corridor mapping, the HP for general purpose mapping, and the HA high altitude variant for wide-area mapping. The CM, HP and HA scanners operate at altitudes of 1.6 km, 5 km and 3.5 km respectively, with a wide FOV of 75° and PPR of 120 – 200 KHz (CM and HA sensors) and 60 – 100 KHz (HP sensor).

Bathymetric LiDAR

Bathymetric LiDARs are designed to capture near-shore bathymetry. They are different to topographic LiDARs in that they use two lasers, one of which is infrared, with a wavelength of 1064 nm to detect the water surface, and the other is green (532 nm) and used to detect the sea floor (Quadros *et al.,* 2008). The water depth is calculated from the time delay between the two return signals (Lin, 1995). Bathymetric LiDARs can measure terrain height but at a lower accuracy and spatial resolution than that of topographic LiDAR. Water depth measurement is affected by turbidity, bottom radiance, incident sun angle and intensity, and use of the technology is limited to water depths of ~25 – 40 m (Quadros *et al.,* 2008). Bathymetric LiDAR is not a stand-alone solution, as hydrographic survey (e.g., using multi-beam echo sounding) is still required for water depth measurement in deeper water and in shallow water with high turbidity (Quadros *et al.,* 2008).

Terrestrial LiDAR

Terrestrial LiDARs are portable, tripod-mounted systems, capable of very high precision measurement (millimetre accuracy). Compared to traditional field survey and airborne LiDAR, they are less expensive, significantly improve in spatial resolution, can map features obscured from the air, and well suited to rapid damage assessments as well as long-term change monitoring and precision modelling (USGS, 2011). It is possible to survey a 360° FOV around the instrument and out to distance of 1.5 km. multiple scans are acquired from different positions so that objects are captured from all perspectives. Sophisticated processing of the ensuing point clouds is required to generate a single coherent scene. Repeat data collection can reveal temporal change in the morphology of features, useful for understanding landscape dynamics and processes of change.

Computational Infrastructure

The sheer volume of data available from the increasing number of satellites, opening up of archives (e.g., USGS Landsat) and extensive time-series from satellites operating beyond nominal lifetime, has spurred the development of automated temporal and bulk processing methodologies (e.g., Dahlhaus *et al.,* 2008; McAtee *et al.,* 2012; Tang *et al.,* 2008), data mining (e.g., Andreea *et al.,* 2011; Vintrou *et al.,* 2013; Zhao, 2012) and data integration techniques (e.g., Bwangoy *et al.,* 2010; Corcoran *et al.,* 2011; Emelyanova *et al.,* 2013; Lu *et al.,* 2011). There are well established methods for time-series analysis that enable drilling down through numerous and diverse data layers (e.g., vegetation indices, DEMs, geology/soil layers) to extract relevant biophysical information to evaluate change. How this type of analysis is incorporated into a computational framework is the focus of current research effort.

The National Computational Infrastructure (NCI) was established in 2007 to advance Australia's capabilities in high-end computational infrastructure and services (http://nci.org.au/). The facility, hosted by the Australian National University (ANU), facilitates intensive data processing and high performance storage, and provides specialised support to research institutions engaged in the development of new technologies and computational frameworks. The NCI system provides the integrated computational environment used by agencies such as Bureau of Meteorology, CSIRO and ANU to address climate change, earth systems science and national water management issues.

As part of the Unlocking the Landsat Archive (ULA) project (2011 - 2013), Geoscience Australia (GA) is transferring its Landsat archive to the NCI and making it freely available under a creative commons license (http://www.ga.gov.au/earth-observation/accessing-satellite-imagery/future-of-landsat-archive.html). By leveraging the capabilities of the NCI, the ULA represents a shift from on-demand processing of raw data to automated bulk processing of standard products (e.g., surface reflectance and fractional cover).

5. MONITORING FRAMEWORK PRINCIPLES AND DESIGN

The opportunities for current and rapidly evolving remote sensing capabilities to address MDBA business needs are considerable. However, for the potential to be fully realised the use of remote sensing must be placed within the broader context of a whole-of-basin monitoring plan, and adaptive management system. Stated another way, the use of remote sensing must be driven by the MDB monitoring plan (rather than the monitoring plan being driven by the capabilities of remote sensing). This chapter presents a number generally accepted principles for environmental monitoring systems and a broad conceptual system design which may be considered. Within this framework, the opportunities and potential for using remote sensing are described for both well-established and emerging remote sensing technology.

We credit many of the ideas and concepts presented to Eyre *et al.* (2011) and Wood *et al.* (2006). Though those references are focussed on rangelands and forests, respectively, the similarity of principles and system design presented in both indicates the high level of commonality among the required fundamentals of environmental monitoring systems.

Framework Principles

In order to fully realise the potential for remote sensing to address operational business needs the current and near-term future capabilities must be placed in the broader context of a Basin monitoring system based on the following principles (adapted from Eyre *et al.* 2011):

1. *Clear desired outcomes*

This would be a strategic statement of high-level goals of the Basin monitoring system. These would be strongly linked to the strategic management goals. An example would be “Facilitate evidence-based environmentally sustainable water trading that also supports economic development across the Basin.”

Impact/use of remote sensing: Low.

2. *Clear management needs*

This would constitute a tactical statement about the information that is required to manage the Basin to achieve the strategic goals. An example would be “Total and seasonal irrigation extractions by state every two years.”

Impact/use of remote sensing: Low.

3. *Clear objectives/questions*

These would be formulated as a link between the strategic-tactical needs and operational information gathering. Their formulation must also consider reporting needs and the target audience for information produced. These objectives or questions would help define tangible information products that the monitoring system would be designed to produce. Specification of the objectives/questions would be a trade-off between the minimum level of detail required to produce fit-for-purpose information, the cost and time required to obtain the desired information, and the relative importance of the objective or question for Basin management. The objectives/questions should be formulated with a general knowledge of the costs, capabilities, and efficiencies of potential information gathering techniques including ground-based sampling, remote sensing, existing data, and collaborative and complementary data acquisition efforts.

Impact/use of remote sensing: High.

4. Conceptual model of Murray Darling Basin system

Management of the Basin and consequent development of an efficient monitoring system is dependent on an understanding of the most important environmental indicators and anthropogenic elements in the Murray Darling Basin, external drivers, and interactions among them.

Impact/use of remote sensing: Low.

5. Sampling design and analysis

Like most environmental monitoring systems, the Basin monitoring system is likely involve collection of a variety of data and information from a range of sources including compilation of information from collaborators and data archives. The sampling design must reflect information costs and priorities which will in turn impact spatial and temporal sampling intensity, and statistical design. The statistical sampling design and analysis is the factor on which remote sensing may have the most impact. This is discussed in a subsequent section.

Impact/use of remote sensing: High.

6. Long-term commitment

Monitoring systems are only effective if maintained over time. The development and establishment of a Basin monitoring system requires an upfront resource commitment for establishment and long-term maintenance and development.

Impact/use of remote sensing: High.

7. Reporting

This relates to the formulation of clear objectives/questions (Point 3). Reporting must satisfy internal management and policy needs, and external queries and certification requirements. Reporting may be significantly limited or enhanced by remote sensing limitations/capabilities.

Impact/use of remote sensing: High.

8. Adaptation

All monitoring systems must be capable of change. In the Basin context, this will be driven by changing internal and external conditions such as management priorities, political, environmental, and regulatory constraints, and also by evolving information gathering techniques and technologies. As remote sensing technology evolves, new types of information will be available and cost-effectiveness will change.

Impact/use of remote sensing: Moderate-High.

9. System evaluation

An in-built activity of any monitoring system should be ongoing system review with the fundamental goal of ensuring that the system is continuing to meet strategic, tactical, and management needs. If the monitoring system has a strong remote sensing component, the effectiveness of remote sensing in meeting Basin information needs must be constantly evaluated. Otherwise the review of remote sensing is a less important part of system evaluation.

Impact/use of remote sensing: Low-Moderate.

10. Collaboration and integration

Because the Basin crosses state boundaries, it is inevitable and desirable that the Murray Darling Basin monitoring system be developed in collaboration with relevant state agencies and activities to minimise duplication of effort and maximise effectiveness of collective investment.

Impact/use of remote sensing: High, Dependent on system design and state activities.

Conceptual Monitoring System Design

A useful way of representing monitoring systems is as an inverted triangle (Figure 5.1) as has been described by Wood *et al.* (2006) and Eyre *et al.* (2011). The broad top indicates the need for landscape level monitoring – i.e., that covers the entire Basin – whereas the point at the bottom acknowledges the need for information that is spatially limited and focused on specific assets. The area in the middle acknowledges the need to connect all information to meet the strategic, tactical, and operational management goals.

The monitoring activities associated with the individual sectors of the triangle need to reinforce each other, and need to combine to address Murray Darling Basin information needs at the strategic, tactical, and management levels. We distinguish between two types of information needs that are not mutually exclusive.

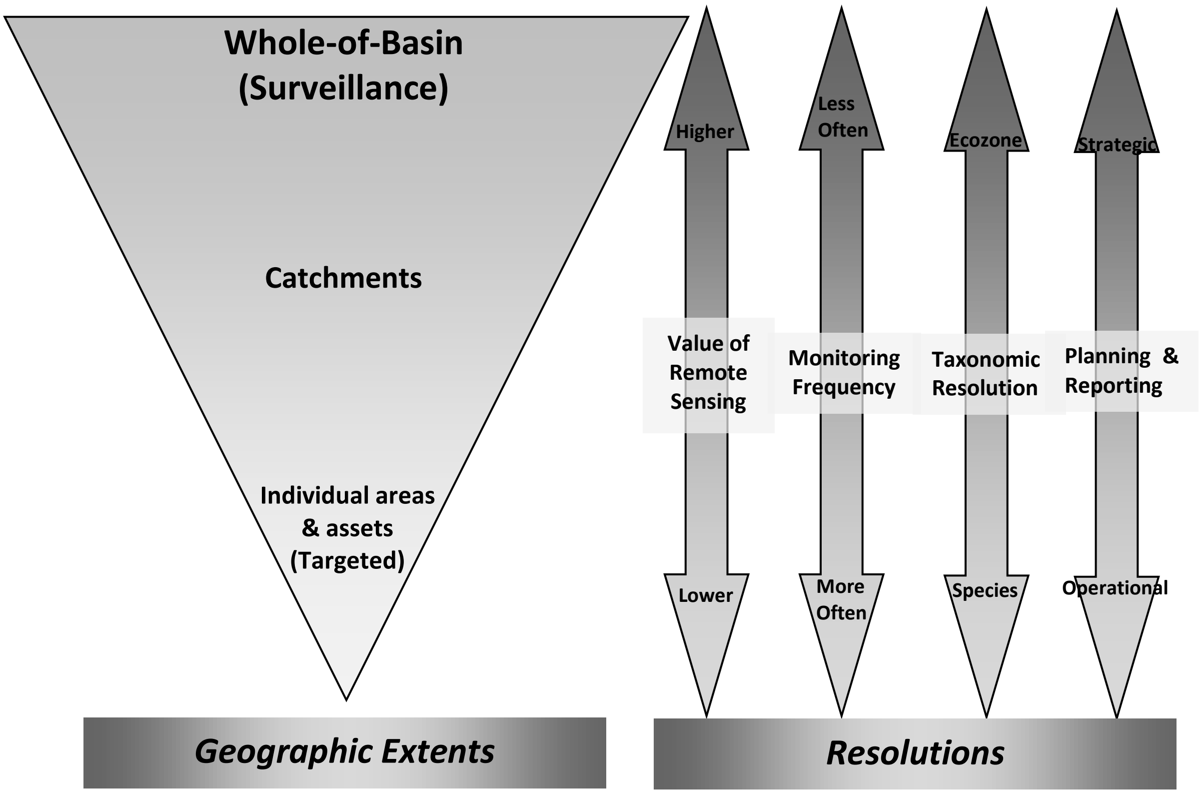


Figure 5.1 Conceptual design of an environmental monitoring system.

Targeted information focuses on relatively specific assets, areas, or characteristics that can be readily defined and identified in the field; it is associated with the lower area of the triangle in Figure 1. Examples would be riparian vegetation, a particular species, or nitrogen concentration in streams. These are things that, because they have been identified as priorities at some level, must have monitoring procedures, protocols and direct or indirect surrogates or indicators designed and implemented that are specific to each. They should be remeasured based on the seasonal and ecological dynamics of the target species, ecosystem or land use.

It is generally assumed that targeted information must be obtained via direct measurement – i.e., field sampling. While this is certainly true for certain things like faunal populations or chemical composition of water resources, it is not necessarily true for others like riparian vegetation. One reason for this is the current and evolving capabilities enable more and better use of remote sensing data as a surrogate for costly field-based data. While direct field-based measurement provides highly detailed information, combining ground-based measurement with information extracted from high resolution remote sensing can be a much more cost-effective way of obtaining targeted information. Indeed, in the field of applied environmental and natural resource statistics, well-established techniques (termed "double sampling") exist for supplementing costly ground-based data with highly correlated information extracted from less expensive information sources such as high resolution imagery (Tickle *et al*., 2006).

Surveillance information focuses on general health and condition; it is associated with the upper area of the triangle in Figure 1. These can be interpreted as indicators or vital signs of general Murray Darling Basin health in the same way that temperature and blood pressure are general indicators of human health. Examples might be woody vegetation cover or the amount and type of land cover conversion. These "vital signs" are monitored periodically with recognition that if one or more has changed or is approaching a critical threshold, more detailed examination of relevant Murray Darling Basin conditions is warranted. This may require purpose-designed studies that are geographically constrained and/or not undertaken on an ongoing basis.

Importantly surveillance monitoring may consist of a combination of appropriate and integrated field-sampling and remote sensing. Monitoring of a broad array of taxa and habitat attributes is likely to always require field-based sampling techniques designed specifically for surveillance monitoring. Appropriate sampling schemes and analytical methodologies can be designed to use remote sensing to enhance and extend ground-based data for targeted information. For example, high resolution remote sensing may play a role in sample-based monitoring of specific habitats, or surrogates such as tree density, or even coarse woody debris. Judiciously collected ground-based data can be used to increase site specificity of coarse resolution remote sensing imagery for surveillance information.

Landscape monitoring can generally be assumed to be derived from remote sensing. And indeed remote sensing is a cost-effective way to obtain a geographic census – i.e., "wall-to-wall" coverage – of the Murray Darling Basin over time. Historically, most wall-to-wall mapping of land cover has been undertaken using moderate to coarse resolution remote sensing (25m-250m). However, with the development of broad-area, high resolution remote sensing it is entirely feasible to map the entire Murray Darling Basin at 2.5-5m resolution on an annual basis, as demonstrated by the New South Wales vegetation monitoring program (Neldner *et al*., 2012)

Finally, given the climatic and seasonal variability across the Murray Darling Basin, specification of the temporal period is critical. For each asset, area, or landscape characteristic, the monitoring period must account for seasonal and climatic variability; land management practices (e.g. double cropping); be short enough to be meaningful for management and reporting needs, but long enough to provide confidence that any change observed is real. Both sample-based information collected on the ground, and wall-to-wall remote sensing data are subject to method-based variability. The monitoring system design must account for the expected level of spatial and temporal variability in what is being monitored and the techniques used to collect data.

6. POTENTIAL FOR REMOTE SENSING TO ADDRESS BUSINESS AND INFORMATION NEEDS OF THE MDBA

While the benefits of remote sensing technologies have long been recognised by the MDBA, and indeed incorporated into some existing monitoring programs, the full capabilities over a range of spatial and temporal scales have not been fully embraced.

The internal workshops and consultation identified 20 broad topic areas which cover the primary business and information needs of the MDBA that may be addressed by remote sensing. For analysis purposes, and to allow the findings of this report to be easily aligned with broader requirements, these needs have been further aggregated according to the National Framework for the Assessment of River and Wetland Health (FARWH), with some additions where necessary.

The following section provides a review and synthesis of the potential for remote sensing to contribute to the primary business and information needs of the MDBA. It draws on previous major reviews, recent published literature, existing operational programs in Australia, an Expert Workshop conducted in December 2012, and further consultation with the State jurisdictions.

Previous Remote Sensing Reviews

A number of major reviews have been previously undertaken which have guided the use of remote sensing in MDBA programs. These include:

- CSIRO. 2003. Determination of SRA Habitat Indicators by Remote Sensing. Technical Report 28/03, April 2003. CSIRO Land and Water, Canberra.
- National Water Commission (NWC). 2007. Australian Water Resources 2005, Assessment of River and Wetland Health: a framework for comparative assessment of the ecological condition of Australian rivers and wetlands. NWC, Canberra.
- Turral, H., Stewardson, M., Wealands, S. and Fee, B. 2008. Potential applications of remote sensing for wetland condition monitoring. A sub-project of NLWRA Project No. DEP19. Wetlands Extent, Distribution and Condition Indicators – South Australia Trials.
- Wealands, S., Stewardson, M., Gilvear, D., Hacker, J., Walker, J., Downes, B. and Rutherfurd, I. 2008. Remote sensing of rivers: a potential contribution to the Murray-Darling Basin Sustainable Rivers Audit. Final Report by the University of Melbourne for the Murray-Darling Basin Commission.
- Cunningham S.C., Mac Nally R., Read J., Baker P.J., White M., Thomson J.R. and Griffioen, P. 2009. A robust technique for mapping vegetation condition across a major river system. *Ecosystems*, 12: 207-219.
- Alluvium Consulting. 2011. Framework of the assessment of river and wetland health: findings from the trials and options for uptake. Waterlines Report Series, Number 58, September, 2011, National Water Commission, Canberra.
- Dekker, A.G. and Hestir, E.L. 2012. Evaluating the feasibility of systematic inland water quality monitoring with satellite remote sensing. CSIRO: Water for a Healthy Country National Research Flagship.

This report provides a synthesis of these reports, which have generally been focused on specific information needs, and then extends the commentary in relation to more recent literature and expert opinion, and operational examples which should be considered by the MDBA in further developing a strategy for fully utilising the potential of remote sensing.

Linking MDBA Business and Information Needs with the Current Remote Sensing Capabilities

In 2003, CSIRO undertook a review of remote sensing capabilities for reporting on the measurement variables identified in the Sustainable Rivers Audit (SRA). Remote sensing was viewed as an important contribution to riparian zone management, both at the time and into the future. Key advantages of remote sensing were identified, including its use in historic analysis, complete ground coverage, high geographic precision, and capacity to reduce the costs associated with high density field sampling and minimise errors due to interpolation or extrapolation of point based measurements (CSIRO, 2003). Remote sensing technologies are not without limitation, and the need for surrogate measures where surface variables cannot be measured directly was recognised.

CSIRO ranked the usefulness of remote sensing to SRA physical habitat and water processes themes as follows:

Operational	Well established image analysis routines and availability of sensors in Australia; map products produced routinely over broad areas; technical expertise and infrastructure available in Australia.
Feasible	Promising case studies but large-scale operational demonstrations are yet to be performed.
Likely	Present data are inadequate for generation of variables, but future availability of methods is anticipated.
Unlikely	Remote sensing is unlikely to measure the variable due to scaling issues or logistics.

For the purpose of this review, the CSIRO approach to ranking has been applied to all identified metrics for the seven key variables related to MDBA information needs. The operational status of each variable is summarised in Tables 6.1 – 6.7 below. Detailed metrics and case study examples are provided in Appendix C - Tables 6.1 - 6.7.

The review is further organised according to the FARWH (NWC, 2007). The seven key variables (physical form, water quality, aquatic biota, hydrological disturbance, catchment disturbance, socio economic and environmental flows) and associated metrics are based on themes identified in the FARWH and SRA Habitat Indicators (CSIRO, 2003) reports, augmented by expert knowledge gained in the MDBA Remote Sensing Workshop (held in December, 2012, Appendix D - Table 6.8) and published literature. It is not suggested that every individual metric be measured, however a prioritised selection would be required to meet the needs of the MDBA. Also included in Appendix E (Table 6.9) is a list of key Australian stakeholders engaged in operational and/or R&D programs utilising remote sensing for monitoring key variables of interest to MDBA.

Physical Form

Characterisation and quantitative assessment of floodplain physical form are feasible using available remote sensing technology (Table 6.1; full details provided in Appendix C – Table 6.1). LiDAR and optical sensors are the key technologies for assessing floodplain and channel form, to inform on flow and inundation relationships along the River Murray and floodplains. Both optical and SAR has also demonstrated the capacity to contribute to flood extent mapping and water body detection.

Effective use of the identified technologies suits a range of applications. Floodplain size, extent and topography provide the basis for flood and hydrological modelling to estimate flood extent and inundation depth. Simulated flood events can assist in determining ecological response and provide input to catchment water management. Floodplain characterisation in terms of wetland habitat, meso habitat diversity and water body type, is important for habitat mapping, biodiversity and water availability assessment. Detailed river channel information is required for hydrological and hydraulic modelling, stream flow analysis and hence flood prediction.

The majority of metrics associated with physical form require a Digital Elevation Model (DEM) as a baseline. The scale and accuracy of the elevation data are dependent on the application. Typically, high resolution elevation data are required in the active portion of the river channel and channel migration zone, and lower resolution data are suitable for the valley floor and areas of minimal relief (e.g., floodplains; Hilldale *et al.,* 2008). LiDAR is the benchmark in aerial DEM generation, with high accuracy, dense height measurement possible over large areas. LiDAR can be used for precise in-channel morphology assessment, although it is limited in areas with very steep and vegetated river banks. Bathymetric LiDAR can be used in non-turbid waters to derive highly detailed river bed and water depth measurement (depending on the size of the channel). The volume of data and processing complexity are gradually becoming manageable through algorithm development and improved hardware capability.

Flood extent and open water mapping are largely operational in Australia, but there are further opportunities to extend on near real time capability for flood and stream flow prediction (Perkins *et al.,* 2011) and water availability monitoring through data integration and when future sensors come online. Moderate resolution optical (e.g., Landsat, Abuzar and Ward, 2003; Shaikh *et al.,* 1998, 2001; Tuteja *et al.,* 2007; Tuteja and Shaikh, 2009) and SAR data (Milne *et al.,* 2008) are used to identify flood events and map inundation extent, duration and vegetation response. A combination of coarse resolution optical (e.g., MODIS), passive radiometer (e.g., AMSR-E) and SRTM DEM data are used for daily monitoring of open water extent and hydrodynamic modelling (Ackland *et al.,* 2012; Gouweleeuw *et al.,* 2011; Karim *et al.,* 2011). Site specific models are under development and improvements to hydrodynamic modelling are being investigated. Commercial optical and SAR satellites which have tasking capabilities offering VHR data and daily re-visit capabilities are currently under-utilised and only used in an ad hoc manner, rather than as part of a formalised on-demand monitoring capability

A range of optical, SAR and LiDAR sensors can be applied to floodplain habitat mapping depending on the scale and transient nature of the features to be mapped. However, data are typically acquired for specific studies and are not collected routinely. Optical indices, SAR and GIS analysis are used for pool assessment (e.g., Tran *et al.,* 2010), and DEMs derived from LiDAR or aerial photography are used to measure water depth (e.g., Feurer *et al.,* 2008). Meso habitat diversity can be characterised through digital analysis of LiDAR and aerial video or other high resolution optical data (e.g., AEA, 2012; Legleiter, 2003; Marcus *et al.,* 2003; Wright *et al.,* 2000). Water body type has been assessed using optical (e.g., Gardelle *et al.,* 2010) and radar data (e.g., Milne *et al.,* 2008).

As well as these broader floodplain scale applications, LiDAR can also be used on a more targeted basis, in channel form assessment, including, for example, analysis of profile shape (e.g., Lin *et al*., 2008) and locating in stream woody debris and macrophytes. Coarse woody debris can also be visually interpreted from aerial photography and aerial video (e.g., AEA, 2012); and not necessarily require a digital solution. Likewise, snag assessment is operational using LiDAR, aerial photography or fine resolution optical data.

Macrophytes, organic matter and sediment type have been evaluated using a range of airborne (including aerial photography and LiDAR) and satellite optical sensors. Levees can be detected using DEMs derived from aerial photography or LiDAR, or classification of high resolution multispectral data (e.g., Steinfeld *et al*., 2012). LiDAR can also be used to inform on processes of channel erosion and scouring (e.g., James *et al.,* 2007; Perroy *et al.,* 2010; Thoma *et al.,* 2005), but ancillary information is required to identify erosion type. Attempts have been made to identify migration barriers and evaluate floodplain connectivity using LiDAR and fine resolution optical data, however further methodology development is required for routine use. Information on the sediment regime, channel movement and gullying (e.g., Hughes and Prosser, 2003) has been assessed using optical sensor, aerial photography and video and LiDAR data, but current methods are inadequate for routine use. Embeddedness, or the amount of fine material around cobbles, requires further research into classification using fine resolution hyperspectral data.

A combination of LiDAR and hydraulic modelling has been used to simulate water depth and flow velocities (e.g., Mandlburger *et al.,* 2009). Shallow and deep ponds have also been mapped using airborne multispectral scanner data and colour aerial photographs (Gilvear *et al.,* 2004). InSAR techniques have also been applied to measure river currents (e.g., Romeiser *et al*., 2011), but the complex and interfering processes and lack of in situ monitoring stations is limiting to routine use.

Since the CSIRO (2003) review of remote sensing capabilities for reporting on the SRA variables, improvements in technology and access to high resolution imagery have increased the confidence in, and feasibility of estimating key parameters. The widespread acquisition of LiDAR and fine scale stereo aerial photography has opened the door for applications development in metrics associated with physical form. Improvements in DEM generation techniques, availability of algorithms, software development and methods for integration with optical data have advanced the use of LiDAR data. Levees and other earthworks can be identified with confidence using DEMs derived primarily from LIDAR, but also aerial photography (hence the authors' decision to upgrade the CSIRO status from 'feasible' to 'operational'). Metrics associated with longitudinal connectivity (upgraded from 'likely' to 'feasible'), potential input of large woody debris ('likely' to operational'), channel movement/gullying, erosion and percent sediment patch ('likely' to 'feasible'), and snag assessment ('likely' to 'operational') have also benefited from the availability of high resolution DEMs derived from LiDAR or spectral unmixing of high resolution optical data. It was thought that estimating the return period of bank full discharge was possible using repeat LiDAR and a flood extent layer (upgraded from 'unlikely' to 'likely'). With advances in bathymetric LiDAR and interferometric SAR (InSAR), the measurement of water current was upgraded from ‘unlikely’ to ‘likely’.

Table 6.1 Summary of usefulness of remote sensing for measuring key variables associated with physical form, as related to MDBA business and information needs.

MDBA information need	**Broad SRA component**	**Typical data sources**	**Key examples**	**Gaps/constraints**
Accurate prediction of flow/inundation relationships along the River Murray and floodplains	Flood and Floodplain extent	ALS S-MsM S-MsC S-Pr SAR	- MDB-FIM flood model (MDBA) - Landsat flood inundation mapping and hydraulic modelling (NOW) - Open water extent/hydrodynamic modelling (CSIRO) - Flood extent mapping (DPI VIC) - Streamflow forecasts (BOM) - PALSAR and TerraSAR-X, wetland dynamics (Milne *et al*. 2008)	- Availability of suitable images - Coarse resolution mapping translates into low accuracy - Limited water gauge records in remote areas for cal/val - Scale of imagery vs. habitat elements
	Pool assessment	A-Ms S-MsF ALB SAR	- Water body detection: optical indices or SAR (Tran *et al*. 2010) - Stereogrammetry and LiDAR: water depth (Feurer *et al*. 2008)	- Water clarity - Overhanging vegetation
	Meso habitat diversity	ALS AV A-Ms A-Hs	- Use of ALS (Hilldale *et al*. 2008) or aerial video data (AEA, 2012). - Airborne MS: map morphologic units (Wright *et al*. 2000). - HS data: map habitat types (Legleiter, 2003; Marcus *et al*. 2003).	- River flow and sensor resolution dependent
	Water body type assessment	S-MsF	- Optical mapping of flooded ponds (Gardelle *et al*. 2010) - PALSAR mapping: ponds and water-filled channels (Milne *et al*. 2008)	- Flow volume dependent
	River bank	ALS	- LiDAR to assess slope stability (Fallsvik, 2007), extract channel cross sections and bank locations, identify bank full stage, measure channel width and bank height (Passalacqua *et al*. 2012), and identify slumping	- DEM accuracy in steep terrain and interpolation error

			and scouring (Kayen *et al*. 2006). - Time-series LiDAR to determine volume change and erosion (Gupta *et al*. 2011)	
	Hydrologic connectivity	ALS AP S-MsM	- Mapping of earthworks (e.g., levees) using LiDAR DEM, Landsat TM, SPOT and aerial photography (Steinfeld *et al*., 2012).	
	Lateral and longitudinal inclusions to migration barriers	S-MsF ALS AP	- Derived from DEMs or classification of MS imagery	- High quality DEM required
	Channel form assessment	ALS AV AP A-Hs S-Hs S-MsF	- Analysis of profile shape using LiDAR (Lin *et al*. 2008) - Aerial video to map in stream woody debris (AEA, 2012) - Macrophytes identified using LiDAR or aerial photography. - Classification using MS or HS data. -VIC DSE (2012) Index of Stream Condition (ISC)	- Benthic mapping determined by water clarity
	Proportions of clay, silt, sand, gravel, cobble, boulders, bedrock and detritus	A-Hs	- Classification of hyperspectral imagery	- Water clarity - Amount of overhanging vegetation
	Potential input of large woody debris	ALS S-MsF	- Classification using optical data or identification using LiDAR VIC DSE (2012) Index of Stream Condition (ISC)	- Method of separating green vegetation and woody material
	Sediment regime assessment	ALS AP	- Predicting gully extent and erosion using aerial photographs (Hughes & Prosser, 2003) and LiDAR (James *et al*. 2007). - LiDAR to detect volume change (Perroy *et al*. 2010; Thoma *et al*. 2005).	- Errors in LiDAR height and depth measurements
	River reach depth assessment	ALB AP A-Ms InSAR	- LiDAR and hydraulic modelling to simulate water depth and flow velocities (Mandlburger *et al*. 2009) - Airborne MS and colour photography to map exposed gravel, shallow and deep water (Gilvear *et al*. 2004). - InSAR for measuring river current (Romeiser *et al*. 2011)	- Lack of in situ monitoring stations
	Snag assessment	A-Ms AP ALS	- Digital classification or identification of LiDAR, AP or fine resolution data. -VIC DSE (2012) Index of Stream Condition (ISC)	- Water clarity - Algal growth on snags
	Embeddedness	A-Hs	- Digital image classification	- Water clarity, biofilms - Overhanging vegetation

(Note: Data sources refer to: Aerial photography (AP), Airborne video (AV), Airborne Laser Scanner (ALS) or LiDAR, Airborne LiDAR Bathymetry (ALB), Airborne Multispectral (A-Ms), Airborne Hyperspectral (A-Hs), Spaceborne Coarse resolution Multispectral (S-MsC), Spaceborne Moderate resolution Multispectral (S-MsM), Spaceborne Fine resolution Multispectral (S-MsF), Spaceborne Hyperspectral (S-Hs), Synthetic Aperture Radar (SAR), Interferometric SAR (InSAR), Satellite Radar Altimetry (S-Ra), Spaceborne passive radar (S-Pr) and Gravity instruments (Gr)).

Water Quality

There is a need within the MDBA to monitor water quality variables in relation to both ecosystem and human health outcomes in relation to Basin Plan targets. Standard variables such as turbidity, total phosphorus and nitrogen, pH, dissolved oxygen and salinity as well as measures of algal biomass are required. Remote sensing demonstrates high potential to contribute to water quality monitoring at a range of spatial and temporal scales (Table 6.2; full details provided in Appendix C – Table 6.2). In particular, the use of optical sensors that record reflectance in the visible, near infrared and thermal infrared wavelength regions offer considerable potential to derive information on water quality variables. Remote sensing applications are less developed however, for mapping algae and biofilms, and catchment salinity monitoring.

At present, the measurement of certain water quality parameters is feasible using available multi-resolution airborne and satellite optical data. These include chlorophyll-a (e.g., Shafique *et al.,* 2003), coloured dissolved organic matter (CDOM, Brando and Dekker, 2003; Dekker and Hestir, 2012), turbidity (Dekker and Hestir, 2012; Jupp *et al.,* 1994a, b), Secchi disk transparency (Dekker and Hestir, 2012) and temperature (Turral *et al.,* 2008). The measurement of additional metrics identified in the FARWH and published case studies are likely using remote sensing data. These include total suspended matter (TSM, Dekker and Hestir, 2012; Jupp *et al.,* 1994a, b; Brando and Dekker, 2003), chlorophyll (Dekker and Hestir, 2012; Jupp *et al.,* 1994a, b), cyanobacterial pigments (Dekker and Hestir, 2012; Jupp *et al.,* 1994a, b) and vertical attenuation of light coefficient (K_d, Brando and Dekker, 2003; Dekker and Hestir, 2012). Algal blooms are more difficult to map, and require good radiometric correction of data and a complex optical model (Turral *et al.,* 2008). Total Nitrogen and Phosphorous content require a proxy measure (Dekker and Hestir, 2012), and their estimation is only considered likely at this stage. It is unlikely that pH and the thickness of a biofilm can be measured using remote sensing. Blackwater events are mapped in real time in the Murray valley, and Landsat imagery acquired before and after events is useful for identification and mapping of extent (Dekker and Hestir, 2012).

Readily available moderate (e.g., Landsat) to coarse resolution (e.g., MODIS, MERIS) optical satellite sensors are most suited to operational water quality monitoring. However the ability to detect small water bodies and narrow river channels at these resolutions is limiting (Dekker and Hestir, 2012). The use of fine resolution satellite optical data (e.g., Quickbird, SPOT-5, RapidEye, Worldivew-2, CASI) is preferable. The extraction of water quality information using optical data is hampered by water turbidity, prevailing weather conditions, bias in temporal observations (due to cloud, haze, fog, smoke or dust), water shading by overhanging vegetation, and the lack of bio-optical information for parameterisation and validation (Dekker and Hestir, 2012). Future launches of Sentinel-2, Sentinel-3 and hyperspectral sensors (EnMAP) will provide new opportunities for satellite based monitoring of water quality (Dekker and Hestir, 2012). The LDCM may also offer new opportunities with the increase from 8 bit to 12 bit data.

Catchment salinity (electrical conductivity, EC) has been monitored using electromagnetic sensors mounted on helicopters and aircraft (Turral *et al.,* 2008). The combination of SAR, hyperspectral and optical imagery and ancillary data for estimating EC has met with some success, but further methodology development is required (Turral *et al.,* 2008).

The measurement potential of primary and secondary indicators of water quality has been downgraded from 'operational' to 'feasible' compared to the CSIRO (2003) review. All metrics can be measured with a moderate level of confidence, with accuracy of retrieval dependent on water clarity and weather conditions. These metrics are already included in SoE reporting, NSW and Murray Darling Basin reporting. While the overall status of the variable: cover of algae/periphyton/biofilm remains unchanged ('likely'), one of the metrics: the proportion of surface covered by algal categories, was upgraded to 'feasible' on the basis of advanced spectral analysis and radiometric correction of hyperspectral data which should improve the capacity for detection. Additional water quality metrics (including blackwater events and catchment salinity) identified in the FARWH trials and published studies were ranked accordingly and included in this review as they contribute to specific information needs of the MDBA.

Table 6.2 Summary of usefulness of remote sensing for measuring key variables associated with water quality, as related to MDBA business and information needs.

MDBA information need	Broad SRA or other component	Typical data sources	Key examples	Gaps/constraints
Water quality in the rivers and floodplains of the Basin	Water processes – primary indicators assessment	A-Hs S-Hs S-MsF S-MsM	- Regression relationships with airborne hyperspectral data (Shafique *et al*. 2003)	- Water turbidity - Weather conditions - Bias in temporal observations due to cloud, haze, fog, smoke or dust - Overhanging vegetation - Limited data for cal/val
	Water processes – ancillary indicators assessment	S-MsC S-MsM S-MsF A-Hs S-Hs	- Use of multi-resolution satellite optical or hyperspectral data to estimate CDOM, turbidity, SD and temperature (Dekker and Hestir, 2012; Turral *et al*. 2008).	
	FARWH water quality metrics	S-MsC S-MsM S-MsF A-Hs S-Hs	- Proxy measures for N and P. - Use of multi-resolution satellite optical and hyperspectral data to estimate TSM (Dekker and Hestir, 2012; Brando and Dekker, 2003; Jupp *et al*. 1994a, b).	- No direct estimation of DO or pH - Mod-coarse resolution data unsuitable for detection of small water bodies and narrow river channels
	Additional water quality metrics	S-MsC S-MsM S-MsF A-Hs S-Hs	- Use of multi-resolution satellite optical and hyperspectral data to estimate CHL, cyanobacterial pigments and K_d (Dekker and Hestir, 2012; Brando and Dekker, 2003; Jupp *et al*. 1994a, b).	- Mod-coarse resolution data unsuitable for detection of small water bodies and narrow river channels
Mapping of algae/blackwater events	Cover of algae/periphyton/biofilm	A-Hs A-MsF AP	- Optical green wavelengths for detecting submerged macrophytes (Turral *et al*. 2008).	- Good radiometric correction - Separation of green signal from water signal
	Blackwater event	S-MsM	- Real time Landsat based monitoring in Murray valley (NOW)	- Difficult to detect change during extreme events
Catchment salinity monitoring	Salinity	S-Hs	- Airborne electromagnetics to map catchment salinity (Turral *et al*. 2008).	- Dynamic nature

(*CDOM: Coloured Dissolved Organic Matter; SD: Secchi Disk transparency; DO: Dissolved Oxygen, N: Nitrogen, P: Phosphorous; TSM: Total Suspended Matter; CHL: Chlorophyll; K_d: Vertical attenuation of light coefficient).

(Note: Data sources refer to: Aerial photography (AP), Airborne video (AV), Airborne Laser Scanner (ALS) or LiDAR, Airborne LiDAR Bathymetry (ALB), Airborne Multispectral (A-Ms), Airborne Hyperspectral (A-Hs), Spaceborne Coarse resolution Multispectral (S-MsC), Spaceborne Moderate resolution Multispectral (S-MsM), Spaceborne Fine resolution Multispectral (S-MsF), Spaceborne Hyperspectral (S-Hs), Synthetic Aperture Radar (SAR), Interferometric SAR (InSAR), Satellite Radar Altimetry (S-Ra), Spaceborne passive radar (S-Pr) and Gravity instruments (Gr)).

Aquatic Biota

Information on past and present ecological condition and response of aquatic biota (including fish, birds and vegetation) to flooding within the basin is core to the business needs of the MDBA, particularly in the Basin Plan and TLM programs. Remote sensing can contribute primarily in the area of vegetation analysis, with the measurement of many vegetation related components operational or feasible given current technologies (Table 6.3; full details provided in Appendix C – Table 6.3). Vegetation metrics including cover of macrophytes, aquatic weeds and riparian and floodplain vegetation extent and structure can be derived using remote sensing data. River condition assessment is undertaken using a combination of indices, some of which can be derived from remote sensing.

High resolution optical data is best applied to map percent cover and patchiness of macrophytes (e.g., aerial video, AEA, 2012; VIC DSE, 2012) and weeds (e.g., Quickbird, Ghioca-Robrecht *et al.,* 2008). Actual species, their abundance and stem density are more difficult to quantify directly using remote sensing data. Surrogate measures are required, including characterisation and mapping of aquatic habitat as an indirect measure of productivity and habitat suitability for sustained population growth (Turral *et al.,* 2008). The presence/absence of habitat features may inform the potential abundance and distribution of fish and bird populations.

A number of metrics are available to describe the complexity, cover and degree of fragmentation of riparian vegetation and habitat. The often narrow extent of features and riparian corridors precludes the use of lower resolution data (Wealands *et al*., 2008). High resolution airborne and satellite optical data (e.g., aerial photography, aerial video and multispectral scanners) increase the opportunities for mapping small-scale vegetation features such as riparian vegetation width (e.g., Arroyo *et al.,* 2010), percent cover including understorey shrubs (Martinuzzi *et al.,* 2009; Turner, 2007; Wing *et al.,* 2012), fragmentation (e.g., VIC DSE, 2012; Apan *et al.,* 2002), and overhanging vegetation (e.g., Arroyo *et al.,* 2010; VIC DSE, 2012). The vegetation must be spectrally distinct and visible from above for routine mapping using optical sensor data. The depth and percent cover of standing litter can be estimated using LiDAR and fractional cover derived from multispectral or hyperspectral data. Age discrimination requires further research using optical and SAR data. Riparian vegetation density, including estimates of basal area and stem density can be estimated from LiDAR DEMs and allometrics. Riparian regeneration can be mapped using LiDAR and classification of digital imagery. Dominant species and vegetation associations can be mapped using airborne hyperspectral data, fine to moderate resolution optical data and LiDAR (e.g., Arroyo *et al.,* 2010; Clark and Healy, 2012). Riparian vegetation extent has been mapped in NSW by the Office of Water (Garlapati *et al.,* 2010) and in Victoria as part of their river condition assessment program (VIC DSE, 2012). Once riparian vegetation has been identified and mapped, various GIS spatial analysis routines can be applied to extract metrics such as distance to channel, vegetated bank length, patch size and length of gaps (VIC DSE, 2012).

More broadly, in the context of floodplain vegetation stands, various approaches to map and model vegetation condition can be applied using airborne and satellite multispectral and hyperspectral sensor data, ALS and SAR. Vegetation condition is defined in many ways and there is no standard approach to the generation of condition metrics. It is generally accepted however, that the reference (baseline) condition need be known, in order to quantify change in whatever form is required (e.g., a loss of biomass over time). Most commonly, optical sensor data (including SPOT, Landsat and MODIS) are used to extract indices to monitor changes in vegetation greenness, wetness and stress (e.g., NSW Office of Water; Cunningham *et al.,* 2009b, 2011; Donohue*et al.,* 2011; McVicar *et al.,* 2010; Turral *et al*., 2008). Victoria DSE use satellite imagery and ancillary data to model native vegetation quality based on the Habitat Hectares approach (VIC DSE, 2007).

Cunngingham *et al.* (2011) developed the Stand Condition Tool to predict the condition of forest and woodlands across Icon Sites in the Murray Darling Basin. An artificial neural network (ANN) was used to determine the relationships between field assessments of stand condition at reference sites and Landsat-5 derived environmental variables (e.g., reflectance and forest type probabilities), and so map stand condition. Model error was calculated by comparing the stand condition scores (SCS) measured in the field with that predicted for the reference sites (obtaining an R^2 = 0.58). Stand condition for each 25 m pixel was classified into five condition classes, ranging from good, moderate, poor, degraded and severely degraded, based on the SCS.

Optically derived vegetation indices have also been used to estimate foliar chemistry (Jones *et al.,* 2013), including nitrogen (e.g., Coops *et al.,* 2003; Barnes *et al.,* 2000; Fourty *et al.,* 1996) and chlorophyll content (e.g., Curran *et al.,* 1990; Datt, 1998; Haboudane *et al.,* 2002; Sims and Gamon, 2002), indicative of canopy stress and plant functioning. Future hyperspectral sensors such as EnMAP will greatly improve monitoring capability of foliar chemistry and routine condition assessment.

Remote sensing demonstrates potential to contribute to river condition assessment, although routine assessment is limited by the lack of available state-wide targeted datasets at the required resolution. The

River Condition Index (RCI) provides the long-term approach to reporting on river health in NSW. The RCI is based on the FARWH approach, and combines multiple indices derived from existing data into single score that can be applied at a range of spatial scales (Healey *et al.,* 2012). The RCI is based on five components, including Riparian Vegetation Cover (FARWH category: Fringing zone), Hydrologic Stress Index (FARWH category: Hydrological change), River Biodiversity Condition Index (FARWH category: Aquatic biota), River Styles Geomorphic Condition Index (FARWH category: Physical form), and Catchment Disturbance Index (FARWH category: catchment disturbance). In stream value (i.e., conservation and ecological value) is also evaluated on a river reach scale using available data (e.g., threatened species, geomorphic condition, conservation priority, recovery potential, key assets). Ecological risk assessments are also undertaken to inform on potential adverse effects of different management decisions (e.g., water extraction and/or physical disturbance). This information is useful for prioritising management and setting water sharing/trading rules. The Index of Stream Condition (ISC), a composite index comprising hydrology, water quality, aquatic life, streamside zone and physical form metrics derived from LiDAR, aerial photography and field survey is applied in Victoria (VIC DSE, 2012).

Further research is required to advance the use of remote sensing technology in predicting, planning and evaluating the ecological response to environmental watering. However, time-series vegetation indices extracted from moderate (e.g., Landsat) and coarse (e.g., MODIS) resolution optical data have been used to determine vegetation response to environmental water (e.g., Sims and Colloff, 2012). The Murray Flow Assessment Tool (MFAT) is one operational example of combining remote sensing derived classification of land cover with ancillary data to predict vegetation types based on a particular flow regime. The use of data acquired by satellite multispectral and hyperspectral sensors has potential to improve vegetation type mapping and in turn improve calibration and application of the model. There is also potential to use remote sensing data to estimate plant water requirements. Hydrology and ecology-driven models are used to determine the environmental water requirements and allocations in wetlands (Davis *et al.,* 2001). Bennett and McCosker (1994) used streamflow records and remote sensing data to establish a relationship between stream flow and area inundated, and so calculated the quantity of water required to achieve inundation of areas of water couch and rushes in the Gwydir wetlands.

Since the CSIRO (2003) review, advances in the processing and analysis of LiDAR and hyperspectral data have increased the capacity to measure certain metrics associated with aquatic biota. The availability of improved tools for filtering and classification of LiDAR data is leading to better estimates of percent cover understorey (‘unlikely’ to ‘feasible’), riparian connectivity (‘feasible’ to ‘operational’) and basal area (‘likely’ to ‘operational’). Species abundance (percent native macrophyte species: ‘unlikely’ to ‘likely’) and fractional cover estimates (percent cover understorey and ground vegetation: ‘unlikely’ to ‘feasible’) are improved through the use of hyperspectral data and advanced unmixing algorithms. Recent methods development in the integration of hyperspectral and LiDAR data is improving the estimation of stem density of aquatic macrophytes (‘unlikely’ to ‘likely’), standing litter (‘unlikely’ to ‘likely’), and percent native species (‘likely’ to ‘feasible’). The integration of LiDAR and hyperspectral or multispectral data is improving the capacity to map regeneration ('feasible' to 'operational'). Vegetation vigour, as defined by CSIRO (2003), is measured using spectral vegetation indices and considered operational. In our review, we replace this term with vegetation condition, and downgrade its measurement to feasible on account of the lack of an agreed definition of condition or standard approach to measurement. Vegetation condition is assessed in operational State vegetation mapping programs, but not necessarily using best practice remote sensing. Additional FARWH metrics included in the review, largely relating to fish and bird populations, are not suitable for measurement using remote sensing. Additional metrics relating to river condition and plant water requirements were included in the review as they met specific needs of the MDBA.

Table 6.3 Summary of usefulness of remote sensing for measuring key variables associated with aquatic biota, as related to MDBA business and information needs.

MDBA information need	**Broad SRA or other component**	**Typical data sources**	**Key examples**	**Gaps/constraints**
Past and present ecological condition and response of fish/birds/vegetation at key environmental assets and between icon sites	Emergent aquatic macrophyte diversity, area and relative abundance	AV A-Ms A-Hs ALS	- Aerial video to capture mesohabitat (AEA, 2012) - Digital image classification	- Overhanging canopy - Water clarity
	Non-vegetation FARWH metrics	S-MsF	- Must rely on surrogates Quickbird to map emergent wetland and invasive species (Ghioca-Robrecht *et al*. 2008).	- No direct RS method of estimating fish/bird richness and % alien/native species. Potentially assess using habitat models (Turral *et al*. 2008)
	Riparian vegetation width	ALS S-MsF	- LiDAR and Quickbird: riparian zone/channel width (Arroyo *et al*. 2010)	
	Riparian vegetation cover	ALS	- LiDAR understory classification (Martinuzzi *et al*. 2009; Turner, 2007; Wing *et al*. 2012).	
	Riparian habitat fragmentation	ALS S-MsM	- LiDAR metrics: stream condition assessment (VIC DSE, 2012). - Landsat TM for quantifying structural change in riparian habitat (Apan *et al*., 2002).	- Vegetation may need to be spectrally distinct.
	Riparian canopy complexity	ALS A-Hs	- LiDAR derived metrics or spectral unmixing	- Shrubs must be spectrally/structurally distinct - Shadowing by trees
	Standing litter component	A-Hs S-Hs ALS	- Spectral unmixing of HS data to retrieve fractional cover - LiDAR to estimate litter depth	- Litter might be obscured by canopy
	Riparian demography	A-Ms ALS A-Hs	- Digital image classification	- Vegetation needs to be spectrally/structurally distinct.
	Riparian vegetation density	A-Ms ALS SAR	- LiDAR height and intensity data, relationships with allometrics.	- Allometrics poorly defined for some species
	Vegetation overhang	A-Ms ALS S-MsF	- LiDAR & Quickbird: overhanging vegetation (Arroyo *et al*. 2010)	- High accuracy geocoded images required.
	Riparian regeneration	ALS S-MsF	- Digital image classification & change detection.	
	Riparian vegetation species	ALS S-MsF A-Hs	- LiDAR (VIC DSE, 2012) and Quickbird (Arroyo *et al*. 2010). - Landsat mapping of riparian forest (Clark and Healy, 2012; Garlapati *et al*. 2010)	- High resolution data may be a requirement.
	Vegetation condition	S-MsF S-MsM S-MsC	- Landsat and SPOT NDVI (NOW) - Landsat Stand Condition Tool (Cunningham *et al*. 2009b, 2011). - Habitat hectares (VIC DSE, 2007). - MODIS greenness indices (NOW)	- No agreed approach - Optical image quality - Reference sites required for calibration of models
	Foliar chemistry (Jones *et al*., 2013)	A-Hs S-Hs S-MsF	- Optically derived veg indices (Datt, 1998; Barnes *et al*. 2000; Fourty *et al* 1996; Haboudane *et al*. 2002; Sims and Gamon, 2002; Coops *et al*. 2003).	
	River Condition	ALS	- NOW River Condition Index (RCI;	- RCI based on existing

		AP	Healey *et al*. 2012). - Index of Stream Condition (ISC; VIC DSE, 2012) using metrics derived from LiDAR, aerial photography and field data.	datasets and limited by lack of state-wide targeted data at required scale
Predicting, planning and evaluating the ecological response to environmental watering	Murray Flow Assessment Tool (MFAT)	S-MsM S-MsC	- RS derived inputs to MFAT (MDBA). - MODIS and Landsat NDVI: vegetation response to flooding (Sims and Colloff, 2012).	- MFAT: poor prediction of veg types based on flow regime. - Low quality of existing vegetation maps.
	Plant water requirements	Ap S-MsM	- Hydrology/ecology approaches to determine environmental water allocations to wetlands (Bennett & McCosker, 1994; Davis *et al*. 2001).	

(Note: Data sources refer to: Aerial photography (AP), Airborne video (AV), Airborne Laser Scanner (ALS) or LiDAR, Airborne LiDAR Bathymetry (ALB), Airborne Multispectral (A-Ms), Airborne Hyperspectral (A-Hs), Spaceborne Coarse resolution Multispectral (S-MsC), Spaceborne Moderate resolution Multispectral (S-MsM), Spaceborne Fine resolution Multispectral (S-MsF), Spaceborne Hyperspectral (S-Hs), Synthetic Aperture Radar (SAR), Interferometric SAR (InSAR), Satellite Radar Altimetry (S-Ra), Spaceborne passive radar (S-Pr) and Gravity instruments (Gr)).

Hydrological Disturbance

Accurate modelling of hydrological change within the Murray Darling basin is core to MDBA operations. In particular, improved estimates of floodplain harvesting and floodplain ET would aid the organisation by improving the accuracy of their surface water models. In addition, improving the characterisation of surface-groundwater connectivity and monitoring groundwater use outside of currently monitored areas would improve accounting and compliance of this resource. Remote sensing capabilities in this realm are feasible with groundwater related components likely given future technological improvements (Table 6.4; full details provided in Appendix C – Table 6.4).

Water loss from evapotranspiration (ET) can be estimated using satellite multispectral data, derived vegetation indices and meteorological data in a model based approach (e.g., Thermal resistance energy balance modelling: Glenn *et al.,* 2011; Guerschman *et al.,* 2009b; Kalma *et al.,* 2008; Van Niel *et al.,* 2012; and spatial variability methods: SEBAL modelling, Turral *et al.,* 2008; Whitfield *et al.,* 2010, 2011, 2012). Open water likelihood (OWL) mapping is feasible using time-series moderate (e.g., Landsat) to coarse (e.g., MODIS) resolution optical data (Guerschman *et al.,* 2011; Emelyanova *et al.,* 2012a, 2012b). Satellite derived metrics, such as albedo, emissivity, LAI and vegetation indices provide inputs to water balance modelling (Band, 2011; Van Dijk, 2010). Current models are limited by their simple representation of the groundwater term and dynamics, which is often inadequate for capturing long term response and interactions with surface water and ecosystems (Band, 2011). Further research is required to develop groundwater models and incorporate satellite derived estimates of vegetation cover and soil moisture into existing models (Band, 2011).

Information on groundwater levels and dependent ecosystems is required for improved characterisation of ground-surface water connectivity and monitoring groundwater levels and use outside of currently monitored areas. Current capability is limited, and only a few studies have attempted to predict ground water dependent vegetation (e.g., NSW Office of Water trialling MODIS, Mitchell *et al.,* 2010) and total water storage change (using GRACE, Doubkova *et al.,* 2011; Tregoning *et al.,* 2012).

Table 6.4 Summary of usefulness of remote sensing for measuring key variables associated with hydrological disturbance, as related to MDBA business and information needs.

MDBA information need	**Metrics**	**Typical data sources**	**Key examples**	**Gaps/constraints**
Estimation of floodplain harvesting and losses from ET	Loss from Evapotranspiration (ET)	S-MsM S-MsC	- Thermal resistance energy balance modelling to estimate ET (Glenn *et al*. 2011; Kalma *et al*. 2008, Van Niel *et al*. 2012; Guerschman *et al*. 2009b). - MODIS hybrid method (CISRO, BOM). - Open water likelihood mapping using Landsat-MODIS blending (Guerschman *et al*. 2011; Emelyanova *et al*. 2012a, 2012b). - SEBAL modelling using RS data and meteorological inputs (Tural *et al*. 2008; Whitfield *et al*. 2010, 2011, 2012).	- Cloud cover in imagery - Large data volume - Validation requires resources
	Water balance modelling	S-MsM S-MsC	- AWRA-L biophysical modelling using RS derived inputs (Band, 2011; Van Dijk, 2010).	- Simple representation of groundwater in models
Improved characterization of ground-surface water connectivity	Groundwater dependent ecosystems	S-MsC	- MODIS time-series indices (EVI, NDMI) to estimate probabilities of GDV (Mitchell *et al*. 2010).	
Monitoring of groundwater levels and use outside of currently monitored areas	Groundwater level	Gr	- GRACE to detect hydrological change (Doubkova *et al*. 2011; Tregoning *et al*. 2012).	- Modelling error - Uncertainty in separation of soil moisture and groundwater - Extensive ground data required.

(Note: Data sources refer to: Aerial photography (AP), Airborne video (AV), Airborne Laser Scanner (ALS) or LiDAR, Airborne LiDAR Bathymetry (ALB), Airborne Multispectral (A-Ms), Airborne Hyperspectral (A-Hs), Spaceborne Coarse resolution Multispectral (S-MsC), Spaceborne Moderate resolution Multispectral (S-MsM), Spaceborne Fine resolution Multispectral (S-MsF), Spaceborne Hyperspectral (S-Hs), Synthetic Aperture Radar (SAR), Interferometric SAR (InSAR), Satellite Radar Altimetry (S-Ra), Spaceborne passive radar (S-Pr) and Gravity instruments (Gr)).

Catchment Disturbance

Accurate assessments of land use, land cover and management at the valley and basin scales are critical inputs into the MDBA's hydrological models. In addition, larger scale vegetation cover maps are required by the MDBA to inform on potential changes to groundwater recharge/discharge through interception and bushfire risk. Current remote sensing technology provides operational as well as feasible options for to deliver information in this area (Table 6.5; full details provided in Appendix C – Table 6.5).

A range of satellite data and methods are available to inform on land cover, land use and land management in an operational manner. Baseline and annual land cover/land use (LCLU) and change (LCLUC) is mapped operationally in a number of state-wide programs using satellite optical data at a range of spatial scales (e.g., Victoria's Land Use Information System, Morse-McNabb, 2011; Queensland's Land Use Mapping Program, ABARES, 2011; Australia's National Carbon Accounting System, AGO, 2002; Furby *et al.,* 2008; NCAS National Forest Trends, Lehmann *et al.,* 2012; National Dynamic Land Cover Mapping, Lymburner *et al.,* 2011). The use of SAR for wall-to-wall mapping of LCLUC and plantations was also demonstrated in Tasmania (e.g., Mitchell *et al.,* 2012). Moderate to coarser resolution data can be used to identify hot spot areas for detailed analysis using high resolution data. Access to time-series data will likely improve mapping accuracies and reduce change ambiguities. Data fusion of optical and SAR may improve on land cover and change mapping. Remote sensing derived land cover, in conjunction with energy use statistics, can provide indication of potential impacts from human activities, as described in the Landscape Development Index (LDI; Brown and Vivas, 2005).

Catchment disturbance arises through fire, human activity (land clearing, land use change, plantation and urban development), climate change and storm damage. Fuel loads have been assessed using LiDAR (e.g., Aardt *et al.,* 2011; Taylor and Roff, 2008) and burned areas mapped using satellite multispectral and SAR data (e.g., Roy *et al.,* 2002). MODIS fire products are produced routinely at global scale, and at near real time for hazard management (Justice *et al.,* 2002).

Methods to describe components of forest vegetation structure using remote sensing technology are relatively well developed (Jones *et al.,* 2013). Forest cover (woody/non-woody vegetation) and vegetation communities are mapped routinely at State and Continental level, utilising available time-series fine (e.g., SPOT-5: NSW SLATS, Hicks, 2012; SPOT-5 and ADS40: NSW OEH Plant Community Type, Denholm *et al.,* 2012; SPOT-5 and aerial photography: Queensland Regional Ecosystems, Neldner *et al.,* 2012; aerial photography: South Australia regional native vegetation extent, DEH, 2006), moderate (e.g., Landsat: Queensland SLATS, Armston *et al.,* 2009; NCAS, Furby *et al.,* 2008; Victoria Ecological Class mapping, VIC DSE, 2007; South Australia regional native vegetation extent, DEH, 2006) and coarse (e.g., AVHRR and MODIS: Continental Forest Monitoring Framework, Wood *et al.,* 2006) resolution optical data. Data acquired by C- and L-band SAR have also been applied to regional scale mapping of forest extent in Tasmania (e.g., Mitchell *et al.,* 2012).

Fine resolution optical data (e.g., CASI and HyMap), aerial photography and LiDAR have proven useful for delineation and mapping of individual tree crowns (e.g., Dalponte *et al*., 2008; Lucas *et al*., 2008; Tickle *et al.,* 2006). Multi-temporal data is useful for mapping seasonally dependent species. The detection of wetland type and species composition is possible using existing optical and SAR data (e.g., DEWNR, 2012; Queensland Wetlands mapping program, EPA, 2005; NSW wetlands mapping, Kingsford *et al.,* 2004; Milne *et al.,* 2008; Tulbure and Broich, 2013). Ground cover monitoring is operational in Queensland (Armston *et al*. 2002; Scarth *et al*. 2010) and NSW (Hicks, 2012) using Landsat derived fractional cover. MODIS derived fractional cover is also available for the whole of Australia (Guerschman *et al*. 2009a).

Various approaches to forest structure assessment have been demonstrated. Tree and forest canopy height estimation is possible using ALS (e.g., Goodwin *et al.,* 2006; Lee and Lucas, 2007; Jenkins, 2012) and InSAR data (e.g., TanDEM-X, Kugler *et al.,* 2011; ICESat GLAS, Lee *et al.,* 2009; and GeoSAR, Williams and Jenkins, 2009). The cost of ALS data over large areas however, is limiting, and there are no currently operational spaceborne LiDARs. Future launches, e.g., IceSAT-2 will provide useful data for sampling ground and canopy height. The accuracy of tree height estimation using SAR interferometry is largely inadequate, due to atmospheric interference, phase noise and temporal decorrelation. TanDEM-X data are used in canopy height modelling, but algorithm development is needed to correct for actual tree height. The main issue is the lack of ground surface height estimation using existing satellite SAR data. Simultaneous acquisition of airborne X- and P-band interferometric measurements by the GeoSAR instrument is currently the best option for tree height estimation. Future satellite SARs and Polarimetric interferometry (PolInSAR) techniques may improve height estimates.

Stand volume, basal area and stem density can be retrieved by establishing empirical relationships between ALS and SAR data and ground measurements (e.g., Clewley *et al.,* 2010; Haywood and Stone, 2011; Kandel *et al.,* 2011; Lee and Lucas, 2007; Musk, 2011; Turner *et al.,* 2011). The accuracy of LiDAR based retrievals decreases in complex forest. Texture metrics have also been extracted from high resolution optical data and related to stand structural parameters (e.g., Ozdemir and Karnieli, 2011; Gomez *et al.,* 2012). The vertical structure of forests has been assessed using aerial photography (e.g., Fensham *et al*., 2002) and ALS data (e.g., Lovell *et al*., 2003; Lee *et al.,* 2004; Lee and Lucas, 2007; Miura and Jones, 2010; Jaskierniak *et al.,* 2011). Leaf Area Index (LAI) can be quantified using ALS (e.g., Armston *et al.,* 2012; Zhao and Popescu,

2009) and satellite optical data (such as MODIS, Knyazikhin *et al.,* 1998). Fraction of absorbed photosynthetically active radiation (fAPAR) is estimated using time-series AVHRR data (e.g., Potter *et al.*, 2005), and has demonstrated potential to inform on large-scale ecosystem disturbance events.

SAR and LiDAR data can be applied to evaluate changes in forest structure, including gains and losses in forest biomass associated with environmental or anthropogenic change. The methods are not yet operational on a large-scale however. Direct estimation of above ground live biomass (AGLB) is possible using LiDAR (e.g., Lucas *et al.,* 2006), however extensive ground calibration is required and allometrics are not always available for all species. Indirect estimation of AGLB has been demonstrated using SAR data (e.g., Lucas *et al.,* 2010), a combination of SAR and optical indices (e.g., Clewley *et al.,* 2010), and using optical data alone (e.g., Henry *et al.,* 2002). The proposed P-band SAR 'BIOMASS' will provide global estimates of biomass at moderate resolution. Australia's National carbon Accounting System (NCAS) is the primary means of estimating greenhouse emission arising from anthropogenic activity on a continental scale (AGO, 2002). NCAS integrates Landsat derived land cover, land use and change, meteorological data, soil type and carbon and land management information in the FullCAM model to estimate emissions (Furby *et al.,* 2008). Limited studies have investigated the potential to map regrowth stage. The integration of ALOS PALAR and Landsat derived Foliage Projective Cover (FPC) has demonstrated potential to map early and intermediate regrowth and remnant forest (Clewley *et al.,* 2012).

Table 6.5 Summary of usefulness of remote sensing for measuring key variables associated with catchment disturbance, as related to MDBA business and information needs.

MDBA information need	**Metrics**	**Typical data sources**	**Key examples**	**Gaps/constraints**
Land cover, land-use and land management	Baseline and annual land cover/land use (LCLU)	S-MsM S-MsF AP SAR	- VIC LU Info System (Morse-McNabb, 2011). - QLD QLUMP (ABARES, 2011). - National LU mapping (Stewart *et al*. 2001) - NCAS Landsat LCLU (NCAS; AGO, 2002, Furby *et al*. 2008). - PALSAR LCLU (Mitchell et a. 2012)	- Spectral separation of land covers
	Land cover/land use change (LCLUC)	S-MsM S-MsF S-MsC SAR	- VIC annual LCLUC (Morse-McNabb, 2011). - National Dynamic Land Cover Mapping (Lymburner *et al*. 2011). - NCAS LCLUC (AGO, 2002, Furby *et al*. 2008). - National Forest Trend (Lehmann *et al*. 2012). - PALSAR LCLUC maps (Mitchell *et al*. 2012).	- Scale and frequency of change must be matched with resolution and temporal frequency of sensor
	Hardwood and softwood plantation	S-MsM S-MsF SAR	- National Plantation Inventory (ABARES). - PALSAR & RADARSAT-2 (Mitchell *et al*. 2012).	- Species must be spectrally distinct
	Landscape Development Index	S-MsF S-MsM	- Integration of LCLU and energy use data (Brown and Vivas, 2005).	
Vegetation extent, type and condition to inform changes in interception and fire risk associated with water reform	Fuel load	ALS A-Hs	- Optically veg indices (Taylor and Roff, 2008). - ALS (Aardt *et al*. 2011).	- Canopy closure - Scaling issues
	Burnt area	S-MsC	- MODIS fire products (Roy *et al*. 2002; Justice *et al*. 2002).	
Mapping of vegetation extent, type and condition to inform groundwater models	Forest cover and extent	S-MsM S-MsC S-MsF ALS SAR	- QLD SLATS Landsat FPC (Armston *et al*. 2009). - NSW SLATS using SPOT-5 (Hicks, 2012). - National Forest Inventory (NFI) - Continental Forest Monitoring Framework (Wood *et al*. 2006). - NCAS (Furby *et al*. 2008). - SAR F/NF (Mitchell *et al*. 2012).	- Spectrally and structurally distinct forest and non-forest classes
	Species composition (Jones *et al.,* 2013)	AP A-Hs	- AP, LiDAR and/or airborne hyperspectral data (Lucas *et al*. 2008; Tickle *et al*. 2006; Dalponte	- Species must be spectrally distinct

		ALS S-MsF	*et al*. 2008).	- Airborne data cost
	Vegetation communities/associations	S-MsF S-MsM AP	- NSW OEH Plant Community Type mapping using SPOT-5 (Denholm *et al*. 2012). - VIC Ecological Vegetation Class (EVC) mapping, Landsat & field data (VIC DSE, 2007). - QLD Regional Ecosystems (RE) mapping, Landsat, SPOT and AP (Neldner *et al*. 2012). - SA regional native veg extent mapping, Landsat, AP and field data (DEH, 2006).	- Consistent time-series data - Seasonal effects and cloud cover in optical imagery - Data volumes - Poor model predictions
	Wetland type	S-MsM SAR	- NSW wetlands (Kingsford *et al*. 2004). - SA mangrove and saltmarsh (DEWNR, 2012). - QLD wetlands (EPA, 2005). - Landsat (Tulbure and Broich, 2013) - Multi-date PALSAR (Milne *et al*. 2008).	- Lack of field data - Low accuracy of existing data layers - Features must be spectrally distinct
	Ground cover	S-MsM S-MsC	- Fractional cover: Landsat (Abuzar *et al*. 2008; Armston *et al*. 2002; Scarth *et al*. 2010; Hicks, 2012) and MODIS (Guerschman *et al*. 2009a)	
	Forest canopy height (Jones *et al.*, 2013)	ALS S-MsM SAR InSAR	- ALS (Goodwin *et al*. 2006; Lee and Lucas, 2007; Jenkins, 2012). - Landsat and PALSAR (Clewley *et al*. 2010) - ICESat GLAS (Lee *et al*. 2009) - GeoSAR (Williams & Jenkins, 2009) - TanDEM-X (Kugler *et al*. 2011).	- Scaling issues from plot to stand - High cost of ALS data
	Stand volume (Jones *et al.*, 2013)	ALS S-MsF SAR	- ALS data (Turner *et al*. 2011; Holmgren, 2004; Yu *et al*. 2010) - High res optical and texture metrics (Ozdemir and Karnieli, 2011; Gomez *et al*., 2012).	
	Basal area (Jones *et al.*, 2013)	ALS	- LiDAR height and intensity data (Haywood and Stone, 2011)	
	Stem density (Jones *et al.*, 2013)	ALS SAR S-MsM	- LiDAR (Lee and Lucas, 2007; Turner *et al*. 2011; Musk, 2011; Kandel *et al*. 2011). - Landsat and PALSAR (Clewley *et al*. 2010)	
	Vertical structure (Jones *et al.*, 2013)	ALS AP SAR	- AP (Fensham *et al*. 2002) and ALS (Lovell *et al*. 2003; Lee *et al*. 2004; Lee and Lucas, 2007; Miura and Jones, 2010; Jaskierniak *et al*. 2011).	
	Leaf Area Index (LAI) (Jones *et al.*, 2013)	ALS S-MsC	- LiDAR (Armston *et al*. 2012; Zhao and Popescu, 2009). - Global LAI, MODIS (Knyazikhin *et al*. 1998)	- Indirect methods more suited to large-scale estimates
	Fraction absorbed of photosynthetically active radiation (fAPAR)	S-MsC	- Time-series AVHRR (Potter *et al*. 2005).	- Coarse resolution limits detection of small-scale disturbances
	Forest biomass and carbon	ALS SAR S-MsM	- LiDAR metrics (Lucas *et al*. 2006). - Landsat, PALSAR and allometrics (Clewley *et al*. 2010; Lucas *et al*. 2010; Henry *et al*. 2002). - NCAS FullCAM modelling (AGO, 2002; Furby *et al*. 2008).	- Limited ground observations - Allometrics not available for all species
	Regrowth stage	S-MsM SAR	- PALSAR and Landsat FPC (Clewley *et al*. 2012).	

(Note: Data sources refer to: Aerial photography (AP), Airborne video (AV), Airborne Laser Scanner (ALS) or LiDAR, Airborne LiDAR Bathymetry (ALB), Airborne Multispectral (A-Ms), Airborne Hyperspectral (A-Hs), Spaceborne Coarse resolution Multispectral (S-MsC), Spaceborne Moderate resolution Multispectral (S-MsM), Spaceborne Fine resolution Multispectral (S-MsF), Spaceborne Hyperspectral (S-Hs), Synthetic Aperture Radar (SAR), Interferometric SAR (InSAR), Satellite Radar Altimetry (S-Ra), Spaceborne passive radar (S-Pr) and Gravity instruments (Gr)).

Socio-economic

Socio-economic indicators under consideration include seasonal irrigated and non-irrigated cropping, irrigation frequency, over-abstraction of water, and basin development, infrastructure and assets. The ability to measure these indicators using remote sensing is feasible to operational in some cases and likely in others given imminent improvements in technology (Table 6.6; full details provided in Appendix C – Table 6.6). Thermal imagery derived from fine to moderate resolution satellite optical data (e.g., Canisius *et al*., 2011) can be used to distinguish between irrigated and non-irrigated cropland, as long as cloud-free images are obtained. The application of SAR is also an option, given the sensitivity of microwaves to soil and canopy moisture. Knowledge of paddock scale crop type and irrigation status can be used to calculate water budgets and hence, irrigation water use over time. Seasonal changes in crop type, including, for example, twice annual (summer and winter) crops can be monitored using time-series moderate resolution satellite optical data (e.g., Abuzar *et al.,* 2008) and SAR(e.g., Witte and Scarth, 2012).

Irrigation frequency can be estimated using thermal infrared data and remotely sensed ET (J. Walker, Monash University, Pers. Comm.). Model approaches that combine remotely sensed vegetation data and crop/water status can be applied to determine the impacts of changes in water use. Routine application of these methods requires further methodology development however, particularly in relation to model-satellite data fusion. Similarly, the application of remote sensing technology to estimating over-abstraction of water requires additional research. Coarse resolution optical data (e.g., MODIS) could be used to compare the volume of water used with the volume of water metered (C. Jones, NOW, Pers. Comm.). This information would be used to identify high risk properties for closer monitoring.

High resolution digital imagery (e.g., ADS40 and SPOT-5 in NSW, Shaikh *et al.,* 2011), aerial photography (e.g., Kim *et al*., 2007) and moderate resolution satellite optical data (e.g., Landsat in Queensland, DERM, 2010) have been successfully applied to mapping farm storages and structures at local to basin scales. Time-series high (e.g., SPOT-5) and moderate (e.g., Landsat) resolution optical data have been used to map changes in the spatial extent of farm dams in the Murray Darling Basin (MDBA, 2008). However, the high cost associated with mapping extensive areas at fine resolution may be limiting and feature detection may be difficult, even using high resolution imagery, depending on the size of features and their clustering in the landscape. Urban development can be monitored using airborne and satellite multispectral imagery, with change in the built and non-built environment used as an indicator of socio-economic circumstance.

Table 6.6 Summary of usefulness of remote sensing for measuring key variables associated with socio-economic indicators, as related to MDBA business and information needs.

MDBA information need	Metrics	Typical data sources	Key examples	Gaps/constraints
Changes in irrigated and non-irrigated cropping over time for: Basin wide estimation of irrigation water use	Irrigated and non-irrigated crops	S-MsM S-MsC SAR AP	- Landsat ETM+ pan data for seasonal land use/land cover mapping (Canisius *et al*. 2011). - National scale mapping of irrigated areas using AP and coarse res images (NLWRA, 2001). - Perennial/annual pasture mapping (VIC DPI). - SAR mapping (MDBA)	- Acquisition of cloud free images - Precipitation effects are significant in SAR imagery
Changes in irrigated and non-irrigated cropping over time for: Assessing and predicting the impacts of the Basin Plan on the seasonal and annual cropping systems	Irrigation frequency	S-MsC S-MsM SAR	- MODIS detection of land areas where water recently applied (NOW). - TIR and remotely sensed ET data (J. Walker, Pers Comm.) - Satellite SAR (MDBA)	- Acquisition of cloud free images - Precipitation effects are significant in SAR imagery
Changes in irrigated	Seasonal changes in crop type	S-MsM	- Mapping perennial and	- Acquisition of cloud

and non-irrigated cropping over time for: Assessing and predicting seasonal changes in cropping and changing socio-economics at the valley scale		SAR	annual pastures using Landsat (Abuzar *et al*. 2008). - Time-series Landsat and ALOS PALSAR data (Witte and Scarth, 2012).	free images
Changes in irrigated and non-irrigated cropping over time for: Detecting potential seasonal over abstraction by irrigators	Over-abstraction of water	S-MsC	- MODIS to compare volume of water used with volume of water metered (NOW).	
Changes in basin developments, infrastructure and assets	Farm storages, bores, levees, plantations, floodplain harvesting infrastructure, plants, industries to assist with WSP development, and development proposals	AP S-MsM S-MsF	- ADS40 and SPOT-5 to map structures and storages (Shaikh *et al*. 2011). - Farm dam development mapped using AP (Kim *et al*. 2007). - SPOT-5 and Landsat to map farm dam extent and change (MDBC, 2008). - Time-series Landsat-5/-7 to map water bodies (DERM, 2010).	- Detection dependent on size of features and spatial resolution of observing sensor - Clustering of dams increases difficulty of detection - Misinterpretation of shadows and black soil - Imagery in non-drought conditions required.
Clearly linking socio-economic changes to water reform through: the identification of predictor variables	Potential indicators: Land use, length of sealed roads in towns, condition of sporting grounds, number of vacant houses, factories, silos, processing plant activity, changes in transport hubs within basin. Also built vs. non-built structures, new development, new roads	A-Ms S-MsM SAR	- Airborne thermal and Landsat imagery - ADS40 (50 cm) to measure town expansion over 5 years	

(Note: Data sources refer to: Aerial photography (AP), Airborne video (AV), Airborne Laser Scanner (ALS) or LiDAR, Airborne LiDAR Bathymetry (ALB), Airborne Multispectral (A-Ms), Airborne Hyperspectral (A-Hs), Spaceborne Coarse resolution Multispectral (S-MsC), Spaceborne Moderate resolution Multispectral (S-MsM), Spaceborne Fine resolution Multispectral (S-MsF), Spaceborne Hyperspectral (S-Hs), Synthetic Aperture Radar (SAR), Interferometric SAR (InSAR), Satellite Radar Altimetry (S-Ra), Spaceborne passive radar (S-Pr) and Gravity instruments (Gr).)

Environmental Flows

Effective planning for environmental releases to achieve site-scale ecological targets and environmental outcomes relies on accurate flow/inundation models and a sound understanding of the current extent, condition and needs of the assets being managed. It also requires the ability to monitor ecosystem responses to support the evaluation of ecological outcomes arising from environmental watering events.

Specific information needs and remote sensing capabilities associated with ecological response to environmental flows, flow/inundation models, and flood extent mapping flows have been summarised in previous sections. This section therefore focuses on the additional key information requirements not yet covered.

Being able to determine the flooding of land associated with natural flows versus managed flows is an important need for the MDBA especially in terms of liability for the flooding of private land. Therefore, improved measurement and monitoring of releases and extractions from storages and river channels is needed to ensure precise compliance and accounting of river operations. Knowledge of the antecedent catchment and floodplain conditions is also required for better prediction of flood timing and inundation extent and duration at site to valley scales and from individual events to seasonal and annual timescales.

Information on the antecedent catchment and floodplain conditions will influence not only the need for environmental water releases, but also their travel through the system once they have been released. Soil moisture is a key component which will influence the antecedent conditions of the catchment.

Current operational methods for estimating soil moisture are limited to assimilation of satellite derived estimates with water balance models to arrive at best informed antecedent basin conditions (WIRADA Project, 2008-2013; Renzullo *et al*. 2012).

Soil moisture has been estimated from remotely sensed data, however, at coarse resolution, which may not be particularly useful as input into hydrological modelling (Table 6.7; full details provided in Appendix C – Table 6.7). Soil moisture estimation is possible using a combination of coarse resolution passive and finer resolution active SAR (Monerris *et al.,* 2011). However extensive ground calibration is required, and algorithm development is complicated by vegetation and surface roughness effects (e.g., Draper *et al.,* 2009; Wigneron *et al.,* 2007; Kerr *et al.,* 2006; Moran *et al.,* 2005; Renzullo *et al.,* 2012). Future dedicated soil moisture mapping missions, including SMAP, and future L-band SARs such as SAOCOM will improve the capacity for soil moisture estimation.

The development of techniques for remotely estimating soil moisture is also severely hampered by a lack of suitable field data. Numerous commercial providers are however, developing cost-effective soil moisture probes equipped with data loggers of telemetry systems. Investing in these technologies offer opportunities for better quantifying the spatial and temporal variability in soil moisture, and the data needed to develop remote sensing methods in the future.

From a flow delivery perspective, water height can be estimated using satellite radar altimetry (Gouweleeuw *et al*., 2011; Jarihani *et al.,* 2012). The scale of features and flood events limits the use of the technology however. Only very large rivers, water bodies and flood events can be captured using existing radar altimeters (e.g., Jason-2/OSTM), as the scale of features is smaller than the resolution of the sensor (~2 km). The temporal frequency (10 days) may also be limiting in highly dynamic environments.

Bathymetric datasets have been collected for a significant portion of the lower Murray channel and Lower Lakes regions using multi-beam sounder and Sonar technologies (Austin and Gallant, 2010). These are currently the most reliable and cost-effective methods for surveying turbid waters. A seamless DEM of the South Australia Murray River was produced using topographic LiDAR and Sounder/Sonar datasets data at a resolution suitable for detailed investigation of water levels, backwater/wetland form and connectivity (Austin and Gallant, 2010).

Bathymetric LiDAR (ALB) data quality is compromised by poor water clarity, very shallow, still water and when the bottom has low reflectivity (Quadros *et al.,* 2008). In Australia, the application of ALB has been restricted to coastal surveys (QLD Government, 2012; Sinclair and Quadros, 2010), and future application in inland water would be restricted to non-turbid environments.

The interpolation of water depths from airborne hyperspectral (e.g., CASI-2, Brando *et al.,* 2009; CASI-2 and Ocean PHILLS, Dekker *et al.,* 2011) and satellite imagery (e.g., Fugro NPA, 2011; ALOS AVNIR-2, Sagar and Wettle, 2010) is also possible, but again restricted to non-turbid waters.

The alternative approach is to derive water height and depth information by acquiring LiDAR or photogrammetric data to produce an accurate DEM in drought conditions when minimal water is in the channel. Then by mapping the extent of future inundation, water height and depth can be derived through simply analyses.

Mapping of flood extent has been demonstrated as an operational capability using airborne and satellite SAR and optical data. However, monitoring flood extent within the context of environmental flows may differ significantly from natural or emergency flood events, notwithstanding the fact that piggybacking on natural high flows is also an effective means of delivering environmental flows. Given the issues associated with compliance and accounting it is unlikely the public good satellites such as MODIS which provides daily 250m resolution products or Landsat which can provide 25m products every 16 days can be relied upon. If information on the extent of flooding from environmental flows is seen as critical, then tasking abilities offered by numerous commercial optical and SAR providers is necessary. Using either VHR satellite optical or SAR platforms daily acquisitions are possible, and in key areas airborne platforms can acquire data on demand.

The Environmental Watering Plans and Annual Water Plans define the assets being targeted and therefore the area to be flooded. Depending on the assets and objectives, the approximate timing of potential events is also known, both in terms of the season and the potential delay from water release to inundation. On an annual and seasonal basis the MDBA therefore has a reasonable understanding of the number, location, duration and planned extent of flooding events. It is therefore possible to develop commercial service level agreements within known budget parameters to cost-effectively acquire and process the necessary data on-demand.

Table 6.7 Summary of usefulness of remote sensing for measuring key variables associated with environmental flows, as related to MDBA business and information needs.

MDBA information need	**Metrics**	**Typical data sources**	**Key examples**	**Gaps/constraints**
Antecedent catchment and floodplain conditions	Soil moisture	S-Pr SAR	- Daily satellite derived top soil moisture products from passive (Windsat, AMSR-E and SMOS, 1978-2018; Draper *et al*. 2009; Wigneron *et al*. 2007; Kerr *et al*. 2006) and active (ERS, Metop ASCAT, 1991-2020) microwave sensors (L. Renzullo, CSIRO). - Assimilation of satellite derived estimates with water balance models to arrive at best informed antecedent basin conditions (WIRADA Project, 2008-2013; Renzullo *et al*. 2012). - Combination of SAR backscatter and forward modelling to estimate soil moisture (Moran *et al*. 2005). - Integration of PLMR (radiometer) and airborne L-band SAR (PLIS) for soil moisture estimation, SMAPEX-3 field experiments in Murrumbidgee catchment (Monerris *et al.,* 2011).	- Coarse resolution - Computational cost - Extensive ground calibration - Decoupling effects of vegetation and roughness on SAR soil moisture estimates
Improved measurement of releases and abstractions from	Water height/depth and flood extent	ALB ALS S- Ra A-Hs	- Combination of ALB and multi-beam echo sounder (QLD Government, 2012). - Integration of ALB and ALS for	- Cloudy/turbid and very shallow water affects ALB measurement - Poor integration of terrain

storages and river channels		S-MsF S-MsM Sonar Multibeam sounder AP	deriving high resolution DEM and water height measurement (Quadros *et al*., 2008; Sinclair & Quadros, 2010; Austin & Gallant, 2010). - Satellite radar altimeter Jason-2/OSTM for measuring water height with ±30 cm accuracy (Gouweleeuw *et al*. 2011). - Multiple laser and satellite radar altimetry for environmental inundation modelling (Jarihani *et al*. 2012). - Interpolation of water depths from airborne and satellite imagery (Dekker *et al.,* 2011; Brando *et al.,* 2009; Fugro NPA, 2011; Sagar & Wettle, 2010).	height acquired by ALS and water depth collected by ALB - Scale of features vs. sensor resolution - Limited satellite track coverage (altimeter) - High resolution DEM collected during drought conditions, and future mapping of water extent offers the most accurate solution. - Public Interest MODIS and Landsat are unlikely to meet compliance and accounting needs of environmental flows. On-demand commercial sensors offer daily acquisition.

(Note: Data sources refer to: Aerial photography (AP), Airborne video (AV), Airborne Laser Scanner (ALS) or LiDAR, Airborne LiDAR Bathymetry (ALB), Airborne Multispectral (A-Ms), Airborne Hyperspectral (A-Hs), Spaceborne Coarse resolution Multispectral (S-MsC), Spaceborne Moderate resolution Multispectral (S-MsM), Spaceborne Fine resolution Multispectral (S-MsF), Spaceborne Hyperspectral (S-Hs), Synthetic Aperture Radar (SAR), Interferometric SAR (InSAR), Satellite Radar Altimetry (S-Ra), Spaceborne passive radar (S-Pr) and Gravity instruments (Gr)).

Summary of Earth Observation Data Use

In general, current remote sensing capability is sufficient to fill many of the MDBA’s business and information needs. However, no single sensor has the capacity to map all the required metrics in a particular theme. Rather a suite of sensors within a multi-scale monitoring framework is recommended to fulfil the MDBA’s business and information needs. Such a scheme might entail (i) regional scale or basin wide mapping utilising high frequency, multi-temporal analysis with AVHRR or MODIS data, (ii) catchment scale, sparser frequency mapping with multi-temporal Landsat, SPOT-5 or SAR data, and (iii) local scale monitoring of high priority sites using finer resolution data (e.g., Quickbird, Worldview-2, digital aerial photography, HyMap and LiDAR). All monitoring requires a baseline or reference condition, at least 5-10 years prior to current site condition, and suitable archives of optical and SAR data are available for this purpose. The availability of a high resolution DEM acquired from LiDAR also provides a valuable baseline. Specific applications may require data from specialised sensors, e.g., soil moisture retrieval from passive radar (AMSR-E and SMOS) and water depth measurement using bathymetric LiDAR.

Sensor selection is application driven and thereby dependent on spatial, spectral and temporal scales of measurement. For the MDBA, these scales range from local site and event scales, to broad variables operating at the entire basin scale over annual time periods. Higher spatial resolution typically incurs higher data volumes and greater computational processing cost. Spatial (geographic) accuracy is also a key factor when pixel-to-pixel change analysis is required. Spectral resolution requirements are related to the diversity of species or materials to be measured. The higher the spectral resolution, the greater the opportunities for discrimination of species and surface types. Satellite multispectral visible-near infrared (VNIR) systems are well established, and more recently hyperspectral imagers (up to shortwave infrared, SWIR) have demonstrated improved discrimination and quantification of biophysical parameters. LiDAR technology has advanced significantly in recent years and is currently considered the benchmark for site survey. Temporal requirements are driven by the frequency and type of change occurring, and the need to investigate seasonal and long-term trends in data for condition assessment. For monitoring purposes, there will always be a trade-off in terms of spatial detail, spectral resolution, mapping frequency and cost (CSIRO, 2003).

The need for complementary on-ground measurement to support calibration and validation of remote sensing data and products is paramount. When working with reflectance data, it is important to capture the variations in spectral response of target species and ground cover. The use of SAR data requires knowledge of ground and meteorological conditions at the time of image acquisition. Ground data supplemented by high resolution imagery (e.g., digital aerial photography) will provide the necessary coverage over extensive and remote areas. Sampling approaches may also use higher resolution imagery to calibrate wall-to-wall mapping approaches using coarser resolution imagery.

More sophisticated monitoring in the future will be afforded with the launch of new sensors and missions, e.g., satellite hyperspectral (EnMAP) for improved mapping of vegetation community composition, habitat change and water quality (Turral *et al.,* 2008), SAR systems (ALOS PALSAR-2, Sentinel, BIOMASS) for land cover, biodiversity and carbon assessment, integrated active-passive radar (SMAP) for soil moisture estimation, and IceSAT-2 for global elevation measurement.

7. STATE HIGH RESOLUTION IMAGERY AND LIDAR ACQUISITION PROGRAMS

Each State jurisdiction within the Murray Darling Basin has mechanisms in place to coordinate and manage the acquisition of aerial and satellite imagery, on behalf of local government, regional bodies such as Catchment Management Agencies and Natural Resource Management agencies, and State agencies. At the Commonwealth level Geoscience Australia also manages The Optical, Geospatial, Radar, and Elevation (OGRE) Supplies and Services Panel. All of these initiatives; were established to allow more efficient and effective acquisition and use of commercial imagery suppliers and geospatial data and services; aim to encourage greater coordination and cooperation within all levels of Australian Government, and have standing procurement arrangements (Contract Panels) in place with service providers.

The following section provides a summary of the mechanisms each Basin State has in place to ensure ongoing acquisition, management and access to high resolution remote sensing products to meet the business requirements of local, regional and state government organisations.

Queensland

Queensland Department of Natural Resources and Mines coordinates the Spatial Imagery Working Group (SIWG) Spatial Imagery Subscription Plan on behalf of the Queensland Spatial Information Council. The plan gives government agencies and private organisation subscribers access to aerial and satellite imagery. Subscribers also have the opportunity to provide input into the imagery acquisition priorities. Through this coordination, duplication of spatial imagery acquisition is reduced. The plan also adheres to the single point of truth concept and aligns with requirements in the *Survey and Mapping Infrastructure Act 2003*.

LiDAR is available for the majority of the QLD coastline (Figure 7.1) and scattered inland areas. High resolution imagery (25 cm or less) is available for the Gulf and Cape regions (Figure 7.2). Significant areas of the QLD portion of the Basin are planned for acquisition in 2013 (Figure 7.3). Whole of Government satellite imagery coverage of QLD is available at very high (e.g., Quickbird, 0.6 m, IKONOS, 1 m) and high (SPOT-5, 2.5 m and 10 m) resolution (Figure 7.4).

Currently Qld Government manages a number of current high resolution imagery and LiDAR datasets over the Basin. SPOT5 2.5m imagery was acquired over the Basin in 2005, 2009 and 2012, under a whole of State Government License. 20 cm aerial imagery was acquired over the major flood prone towns in 2011, and 60cm imagery was acquired in 2003 over most of the Basin. 50cm imagery is being acquired in 2013 for much of the eastern part of the Basin and the Surat Basin. LiDAR surveys have also been completed over flood prone towns and floodplains since the 2011 floods.

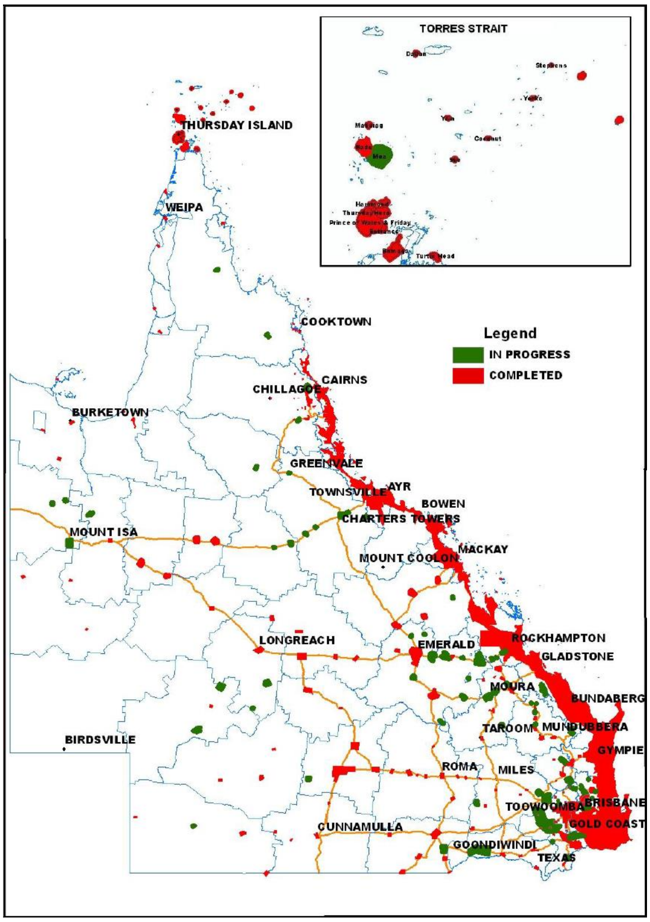


Figure 7.1 Queensland LiDAR coverage (http://www.nrm.qld.gov.au/property/mapping/dtdata/pdf/all-lidar-dem-6-12-v7.pdf).

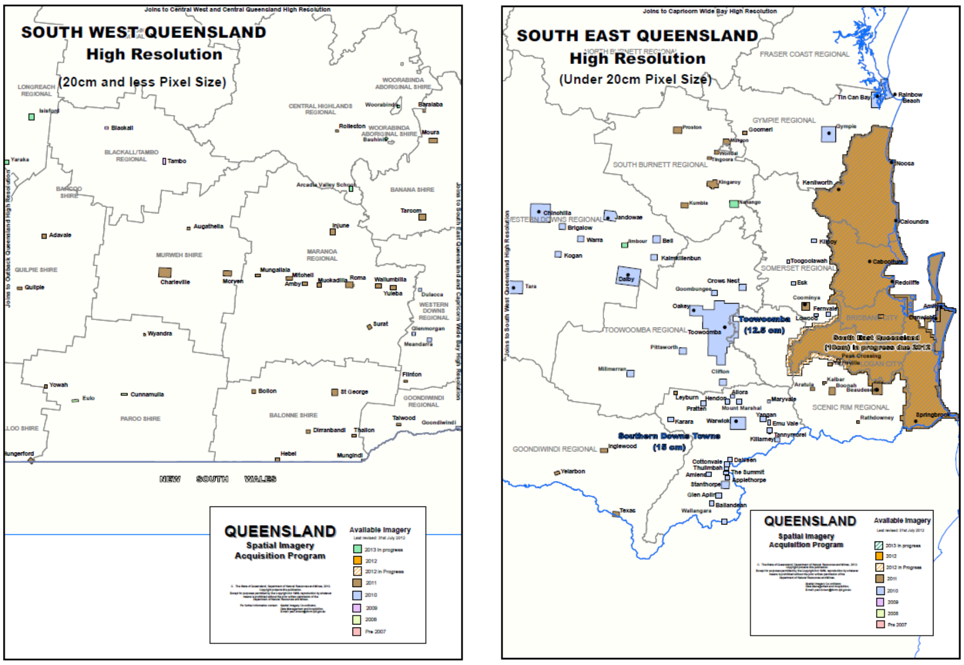


Figure 7.2 Queensland <20cm resolution aerial imagery coverage (http://www.nrm.qld.gov.au/property/mapping/ortho_keymaps/pdf/ortho-map-2012-v1.pdf).

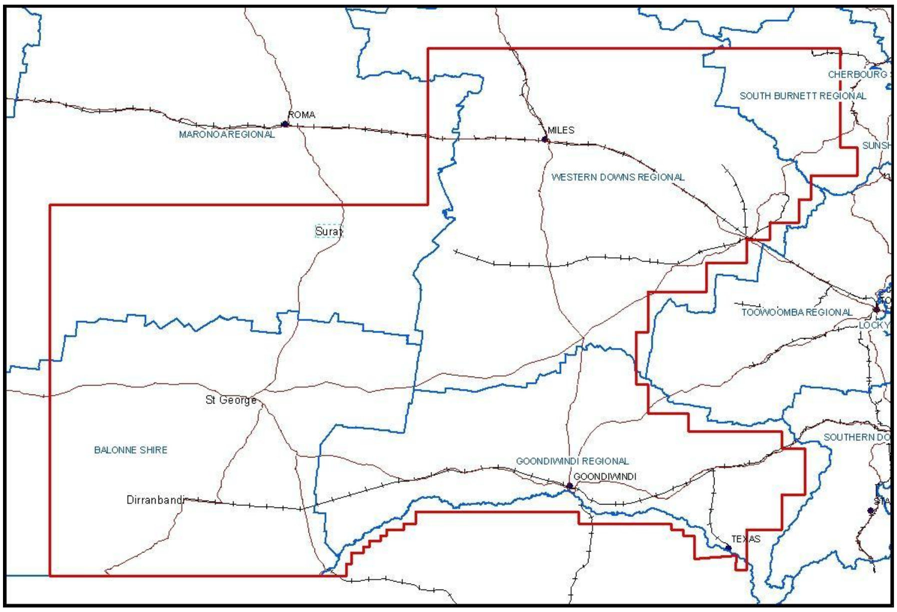


Figure 7.3 Queensland 2013 planned aerial imagery acquisition.

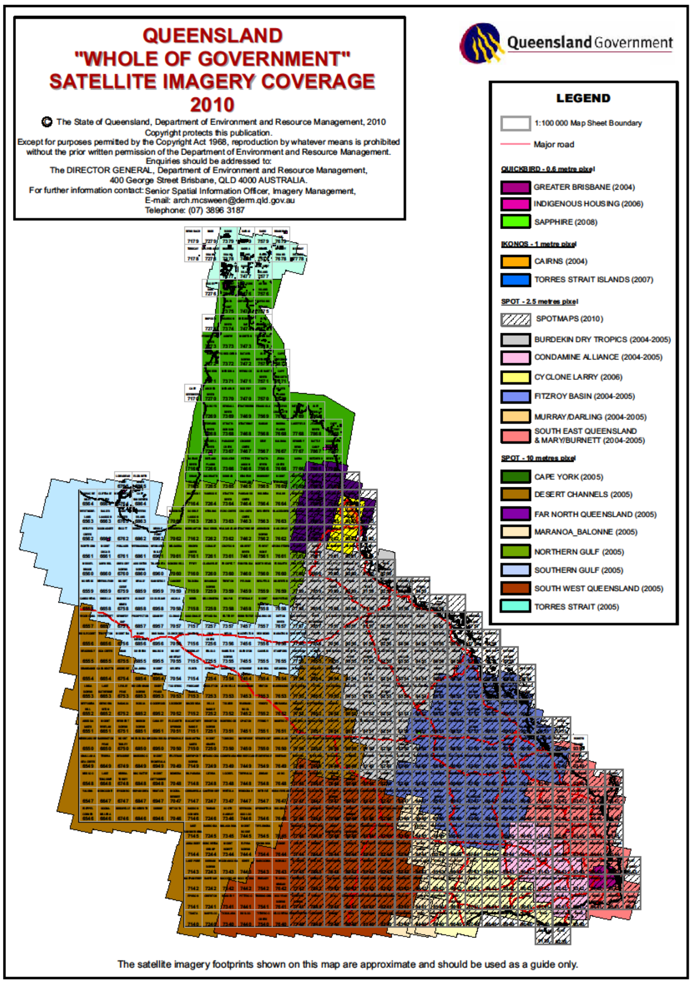
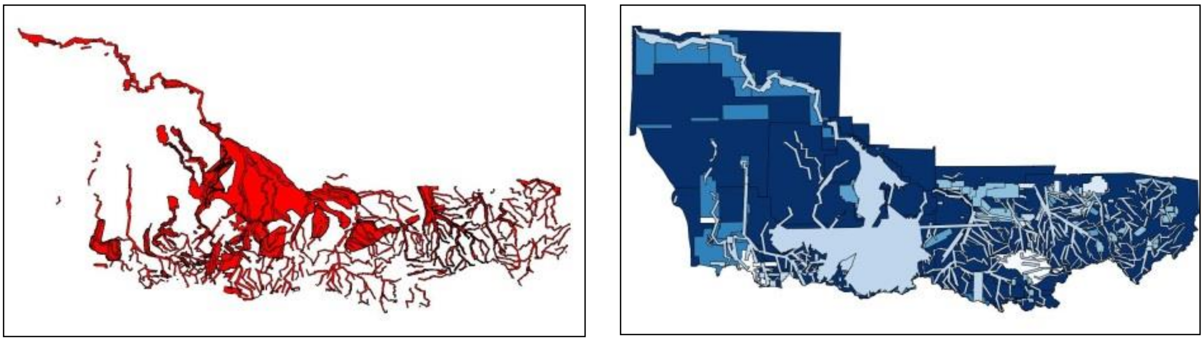


Figure 7.4 Queensland high resolution whole-of-government satellite imagery coverage (http://www.nrm.qld.gov.au/property/mapping/pdf/wog_satellite_index_map2.pdf).

Victoria

The Victorian Department of Sustainability and Environment runs the Coordinated Imagery Program (CIP) on behalf of the Victorian Government. While there is no fully funded annual program, the CIP calls for expressions of interest across all levels of government for the acquisition of LiDAR and imagery, and requests a notional budget commitment from potential investors. An overall program is then put out to a Panel of contractors with the aim of achieving significant economies of scale, and to identify potential collaborators to fund the acquisitions. DSE then manages the procurement, acquisition, quality assurance and distribution of the data. In recent years around $2 million per year has been spent on high resolution imagery and LiDAR.

In 2009-10, The Victorian Statewide Rivers Project acquired LiDAR and high resolution imagery over all major rivers and floodplains, one of the most significant single programs undertaken to date over approximately 30,000km^2(Figure 7.5). The Statewide Land Cover Project also acquired 50cm aerial photography over the State in 2009-10, along with numerous other higher resolution datasets prior and after this acquisition. In addition 5m RapidEye Satellite imagery was also acquired across the State in 2009.



Current LiDAR coverage

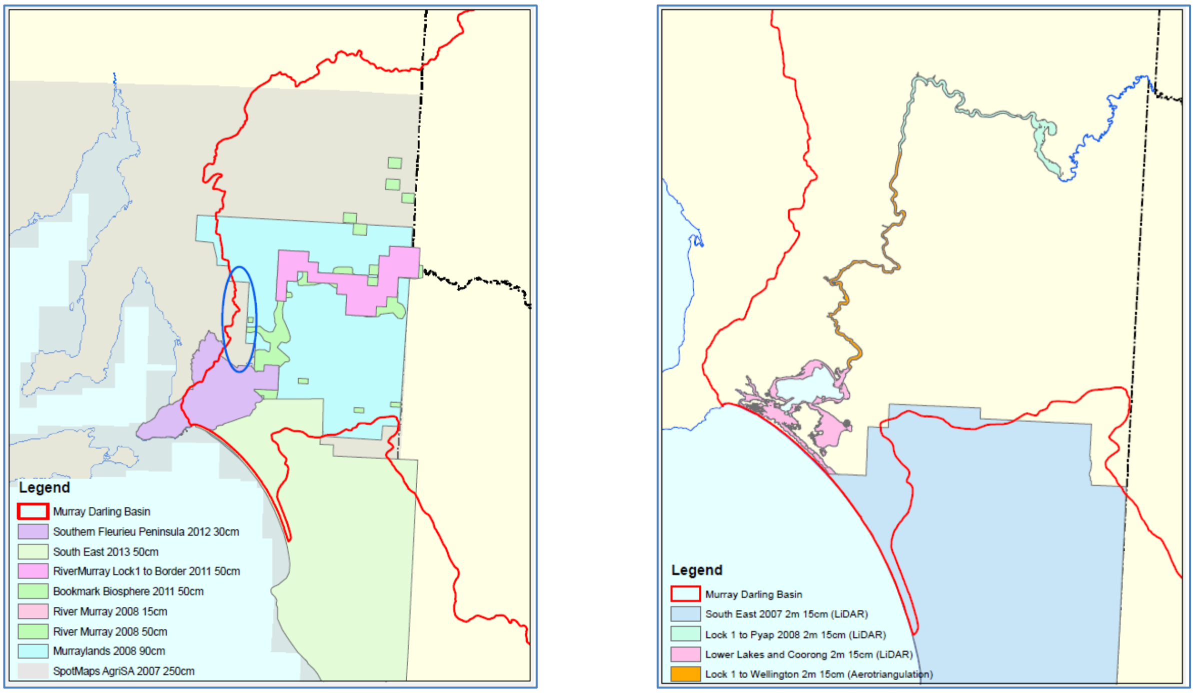
Current high resolution imagery coverage

Figure 7.5 Availability of LiDAR and high resolution imagery over Victoria.

South Australia

The South Australian Department of Environment, Water and Natural Resources (DEWNR) coordinates imagery acquisition across the South Australian Governments. Like most other states, the funding is generally project-based, but generally most areas within the Basin are acquired with high resolution aerial or satellite imagery at least every five years. New imagery has been acquired over the southern Fleurieu Peninsula and the south east of SA at 30cm and 50cm respectively in December 2012 and January/February 2013. Imagery over the River Murray corridor between Lock 1 and the SA Border was acquired early in 2011. The remainder of the basin area in SA has had no update since 2007/08 when 2.5m SPOT5 imagery was acquired. There is a tentative proposal for an acquisition early in 2014 that will update the River Murray Corridor, at around 50cm spatial resolution. This may be extended, budget permitting.

High resolution DEM data acquired from LiDAR and aerial photography in 2007-08 is largely restricted to the River Murray and the South East of SA. There are currently no plans for new acquisitions.



Recent high resolution imagery		Recent high resolution elevation data

Figure 7.6 Availability of LiDAR and high resolution imagery over South Australia.

New South Wales

NSW Land and Property Information (LPI) is responsible for the capture and acquisition of a new and improved statewide elevation and imagery datasets, in collaboration with the Office of Environment and Heritage (OEH).

Since 2004-05 the OEH have been acquiring annual statewide coverage of SPOT-5 25m satellite imagery. There are now eight epochs of 2.5m multispectral imagery for the entire NSW area of the Basin. This imagery has been used as part of vegetation compliance monitoring, production of woody vegetation extent, Projective Foliage Cover Products, and more recently fractional cover products, in combination with time-series Landsat data. At the present time only one of the eight epochs are licensed for Australian Government use.

LPI operate an airborne ADS40/80 digital imaging sensor as part of ongoing imagery acquisition program. 50cm resolution aerial imagery has been acquired for the entire eastern half of the state since 2008 using the ADS40/80 sensor, which provides four-band multispectral imagery (Figure 7.7). Higher resolution imagery was also captured over flooded inland towns in 2010.

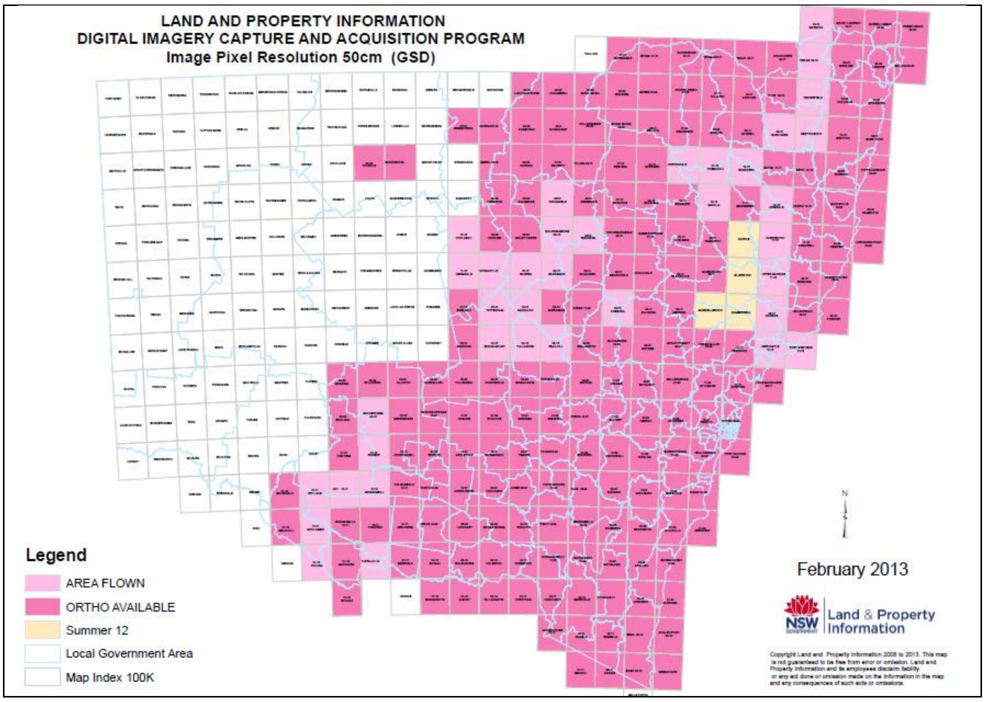


Figure 7.7 High resolution aerial imagery capture by NSW LPI.

LPI also operate a Leica ALS50-2 airborne LiDAR sensor. To date the forward program has emphasised the capture of high resolution LiDAR derived data along the entire East Coast of NSW, which generally follows the 10m contour line and below, as well as "at risk" urbanised areas and hotspots in inland river systems (Figure 7.8). This LiDAR is captured in logical project areas of no greater than 1000 sq. km's and complies with ICSM Acquisition Specifications.

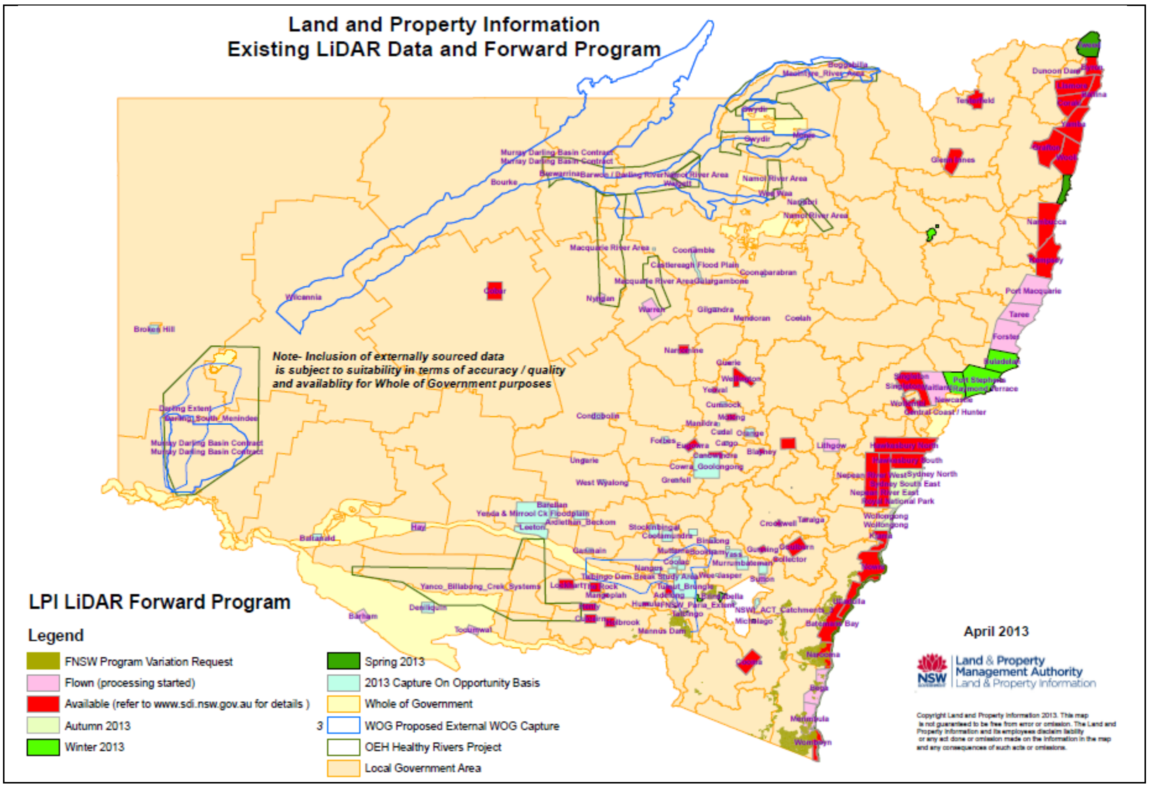
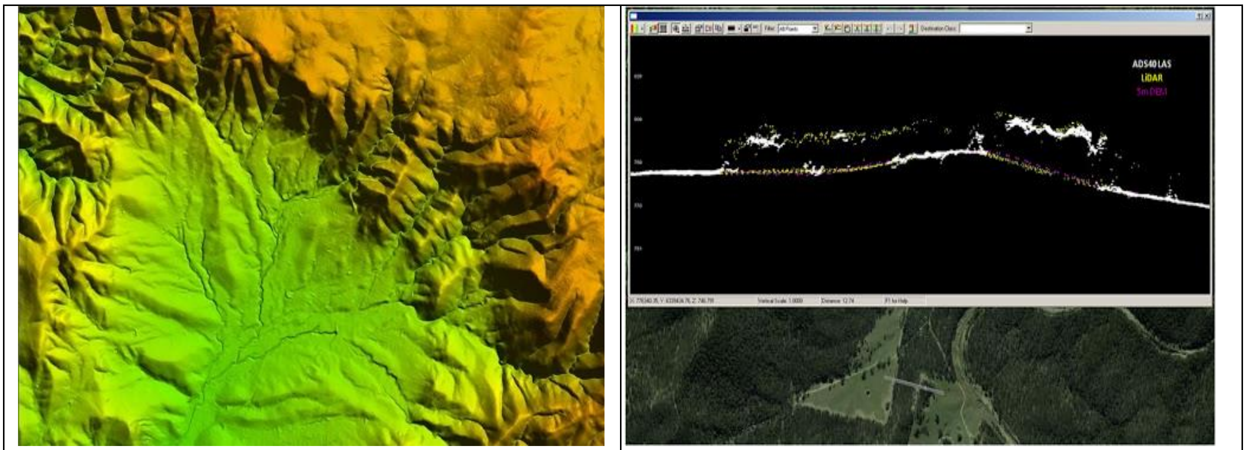


Figure 7.8 LiDAR capture by NSW LPI.

LPI has also been assessing the use of the ADS40/80 sensor to generate high resolution DEMs from the optical stereo sensor using "point cloud" techniques currently utilized for processing LiDAR data. This has allowed LPI to use LiDAR related techniques to explore opportunities for new 3D data products. Initial results are very encouraging with contractors engaged to; classify the point cloud into ground, vegetation and structures, extract features such as buildings and water bodies, and produce bare-earth DEM modules (Figure 7.9). Comparisons with LIDAR "ground truth" show the data as coincident, however no penetration of dense vegetation due to the source being photogrammetry. Comparisons with bare-ground check points show the global vertical accuracy to be sub-metre (95% confidence); however the local relative accuracy is much better.



Bare-earth DEM (5m resolution)

ADS40 Classified point cloud profile

Figure 7.9 Generation of bare-earth DEMs and feature classification using point cloud techniques applied to ADS40/80 data (NSW LPI).

8. MAJOR STATE AND NATIONAL MONITORING INITIATIVES AND PROGRAMS

This section presents a summary of existing operational mapping and monitoring programs that utilise remote sensing to meet national, state, regional and local information needs. A number of examples are provided where remote sensing has been successfully applied to answer questions similar to those posed by the MDBA. National initiatives that align with MDBA business and spatial information needs are also outlined. There are many potential avenues for collaboration between regional, State, and Australian Government agencies and MDBA, and these opportunities are discussed.

New South Wales

Vegetation mapping

State-wide vegetation mapping in NSW is the responsibility of the Office of Environment and Heritage (OEH). The OEH remote sensing program is driven by the need for state-wide information on vegetation communities to guide legislation and policy development, regulation and compliance and support regional planning by Catchment Management Authorities (CMAs).

Previous state-wide vegetation layers (including vegetation extent, vegetation condition and pressures affecting native vegetation) were compiled using existing data sets to meet the needs of State of the Catchments (SOC) 2010 reporting (Dillon *et al.,* 2011). Native vegetation extent was derived from the (i) Intact vegetation v2 layer (Keith and Simpson, 2006), where native woody vegetation and grassland were mapped using field survey data collected over 1970 - 2005, and (ii) NSW Interim Native Vegetation Extent v1 2008 (DECC, 2008), produced using QLD SLATS methodology applied to Landsat TM/ETM+ data to quantify Foliage Projective Cover (FPC). Only four Landsat epochs were used to generate FPC values however, and data were acquired in particularly dry conditions which likely led to underestimated woody vegetation from FPC. FPC data were also only calibrated for QLD and not NSW.

Vegetation condition was compiled using the vegetation extent layer described above, merged land use, NSW NPWS Estate, Forests NSW Estate, and NSW Travelling Stock Reserves layers. OEH has since initiated a state-wide vegetation condition monitoring, evaluating and reporting (MER) program to collect site data across a range of land cover, land use and management scenarios, for use in modelling and improving the mapping of vegetation condition (Dillon *et al.,* 2011). Vegetation pressures were compiled using the merged land use and ancillary layers, and categorised according to conservation/natural environment, production from natural environments, dryland or irrigated agriculture and plantations, and intensive uses. Ongoing data collection and OEH's involvement in the National Dynamic Land Cover Mapping project is anticipated to address some of the shortcomings of the vegetation pressures mapping approach (Dillon *et al.,* 2011).

Operational procedures are now in place to produce standardised state-wide mapping of woody and non-woody vegetation extent and change, plant community types (PCT) and groundcover. Current approaches are outlined below.

The overall approach to mapping PCTs combines classification and spatial processing in a series of interrelated process modules (described in detail in Denholm *et al.,* 2012). Woody vegetation is mapped using an object-based, unsupervised classification of multi-temporal pan-sharpened SPOT-5 data. Map products are validated by visual comparison of the woody component in ADS40/80 or SPOT-5 imagery. Woody vegetation objects are attributed with PCTs using species distribution models and expert rules using floristic survey (plot data), remote sensing and environmental (ancillary) data. A centralised database, the NSW Vegetation Information System (NSW VIS) has been established for storage of all native vegetation data (including relational databases for the PCTs, floristic site survey data and a catalogue of vegetation maps).

The NSW regional vegetation mapping relies on SPOT-5 data, due to its high spatial resolution (2.5 m panchromatic, 5 and 10 m multispectral), multispectral content (VNIR-SWIR) and multi-temporal coverage available from 2004-2011. The time-series is exploited to minimise differences between images and improve the accuracy of native vegetation products. The large volumes of data also require substantial and high-speed storage. ADS40 digital imagery (50 cm resolution), time-series Landsat (1989 - 2010) and LiDAR (captured at various times) data are used in the mapping process.

The method was designed to exploit the time-series multispectral data afforded by SPOT-5 and existing vegetation mapping and environmental layers in the absence of available and extensive field survey data. Gaps exist where field survey and records are absent, or are poorly sampled and therefore not representative of the diversity of communities (Denholm *et al.,* 2012). Priority areas for gap filling include parts of the Central Western slopes, Southern Highlands/Alps and all Western regions of NSW.

Continuous improvement of the PCT program is facilitated through consultation and open workshops with experts and practitioners. The system is intended to be systematic, transparent and repeatable for practical application across NSW (Denholm *et al.,* 2012).

Using the approach outlined above, approximately 35,000 km^2 of the Murray CMA, including 100 vegetation classes have been mapped (Figure 8.1). Validation is not complete. However 65 % of independent surveys are considered correct (Source: A. Roff, OEH).

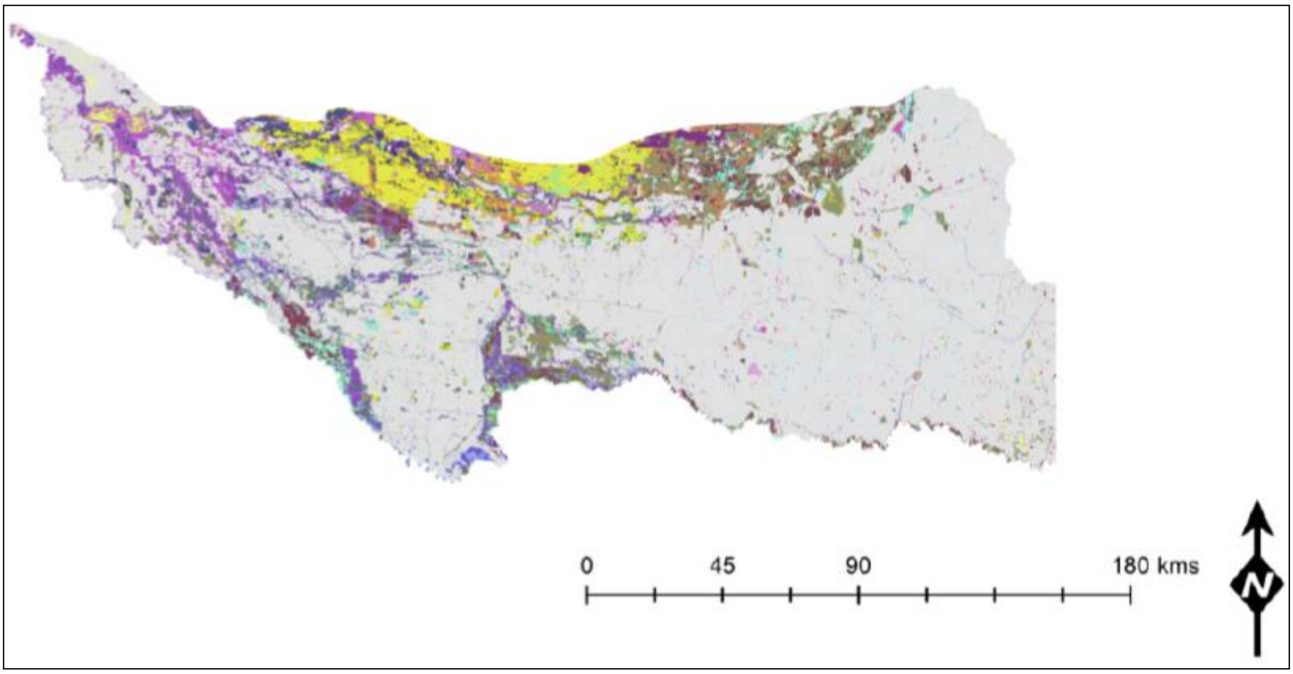


Figure 8.1 Vegetation community mapping in Murray CMA, v2, 2010 (Source: A. Roff, NSW OEH).

Statewide Landcover and Trees Study (SLATS) NSW

The QLD SLATS approach to woody vegetation change mapping has been applied in NSW. The approach is based on semi-automated classification of calibrated Landsat time-series vegetation indices and visual editing of change data using SPOT imagery. The SLATS methodology has since been modified to take advantage of available high resolution SPOT-5 data for NSW, and processing is running in parallel to the Landsat (Hicks, 2012). Atmospheric, Bi-Directional Reflectance Distribution (BRDF) and topographic corrections have been applied to SPOT-5 data, and masks for cloud and water have been developed. SPOT FPC products are derived by cross-calibration with Landsat FPC products using data calibrated for QLD and have not been validated. A time-series of four state-wide SPOT FPC mosaics will be generated using data acquired since 2008 (e.g., Figure 8.2). The availability of time-series SPOT FPC will facilitate high resolution state-wide mapping of woody vegetation extent and change for monitoring and compliance purposes, and potentially provide an alternative approach to mapping woody/non-woody vegetation in NSW.

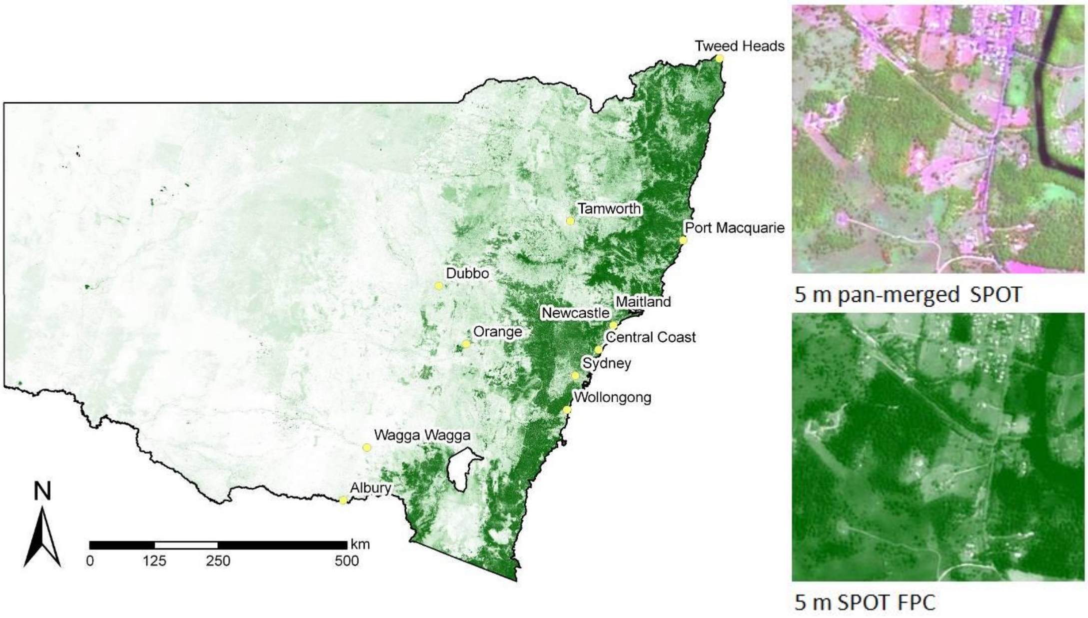


Figure 8.2 SPOT-5 derived Foliage Projective Cover (FPC) for NSW. Subsets highlight detail in pan-sharpened SPOT-5 and derived FPC data (Hicks, 2012).

Regional monitoring of ground cover by CMAs is based on Landsat derived fractional cover, with local validation (Hicks, 2012). Map outputs present the trend in fractional cover for sub-catchments and land management units (e.g., Figure 8.3). Fractional cover products are used to monitor ground cover to inform catchment action plans and on-ground projects.

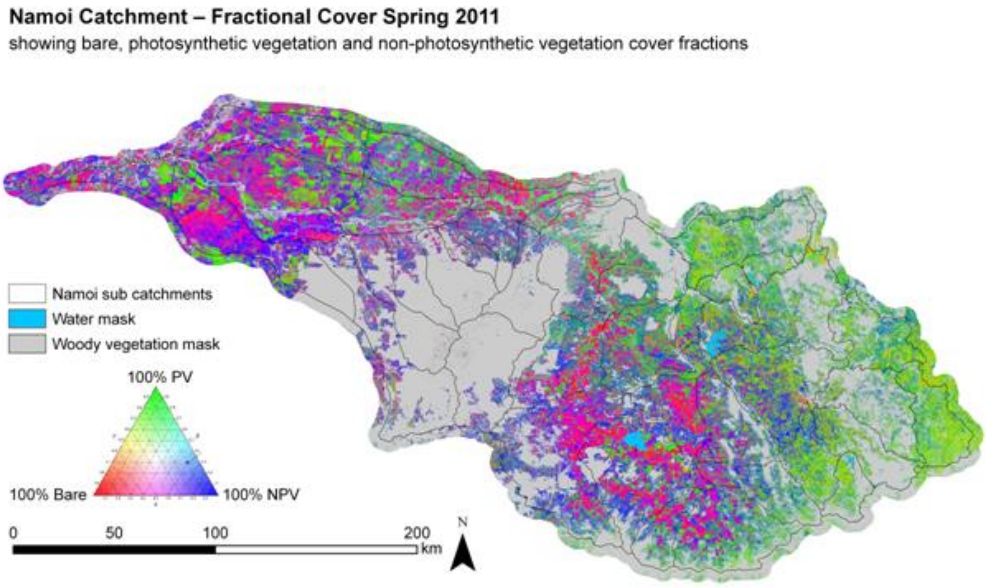


Figure 8.3 Fractional cover product derived from time-series Landsat imagery, Namoi catchment (Hicks, 2012).

Catchment Monitoring, evaluation and reporting

The NSW Office of Water (NOW) is charged with the strategic management of the State's freshwater resources. NOW responsibilities include developing water policy and water sharing plans, determining water allocations, approving water abstractions, use and trading, monitoring water quality, the health of aquatic ecosystems and river and groundwater condition (http://www.water.nsw.gov.au/Water-Management/default.aspx). Monitoring, evaluation and reporting on the status of rivers and groundwater is required for the State plan.
(http://www.water.nsw.gov.au/Water-management/Monitoring/Catchments/default.aspx).

The sustainable management of groundwater-dependent ecosystems is a requirement of the NSW Water Management Act 2000 (Mitchell *et al.,* 2010). Limited tools are available for identification of groundwater-dependent terrestrial vegetation (GDTV) at larger than site scale, and hence the ability to protect these systems is limited. NOW is investigating several approaches to identifying areas that are potentially groundwater dependent. The variation in vegetation greenness and moisture over time (2000 – 2009) has been assessed using a MODIS-derived Enhanced Vegetation Index (EVI) and Normalised Difference Moisture Index (NDMI) respectively. This information, combined with a Landsat-derived crop and woody vegetation mask are then used to identify potential areas of GDTV (e.g., Figure 8.4; Mitchell *et al.,* 2010). The theoretical basis for the approach stems from the observation that landscapes potentially dependent on groundwater sources are more likely to have consistently high wetness and greenness and low stress conditions (NOW, 2012). Improvements to the process are ongoing, and include the integration of land surface temperature, soil moisture modelling, generation of a water table map, field work and validation using Landsat imagery (NOW, 2012).

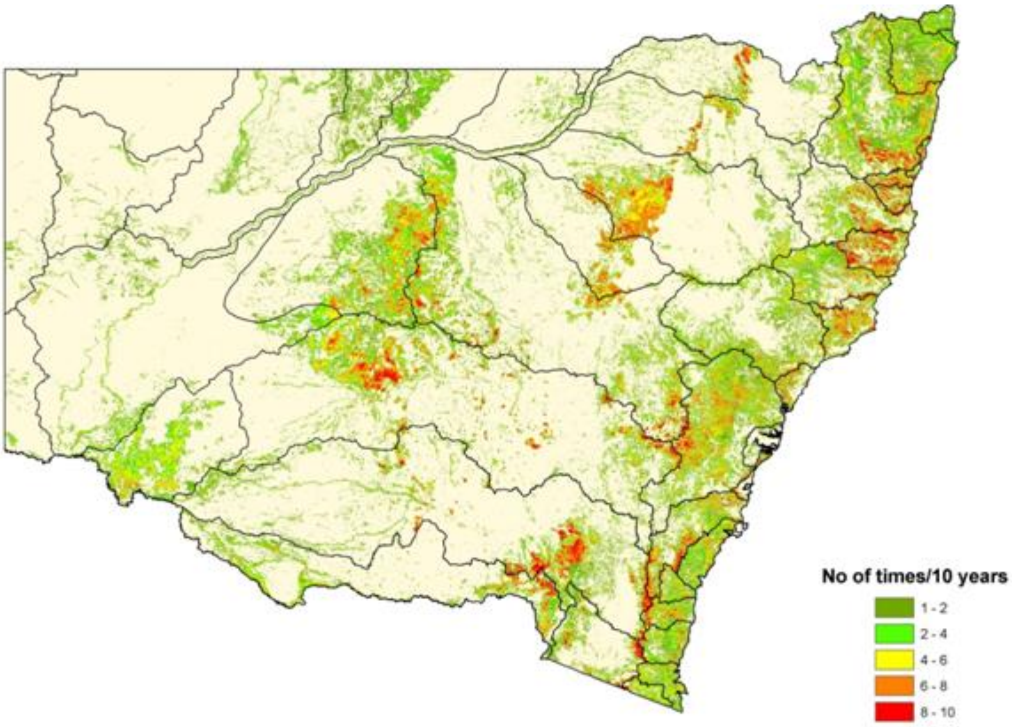


Figure 8.4 Dependency of terrestrial vegetation on groundwater sources derived from analysis of 16-day interval MODIS data collected over the past 10 years (NOW, 2012).

The NOW developed the NSW River Condition Index (RCI) for long-term reporting on river health, as directed by the National Water Commission. Other spatial products developed include measures of in stream value and risks to in stream value (i.e., resilience) from disturbance and water extraction. The RCI is based on the National Framework for Assessing River and Wetland Health (FARWH) approach, wherein multiple indices are combined into a single condition score that can be applied at the required spatial scales (Healey *et al*., 2012). River condition sub-indices are standardised using the Euclidean distance measure (Norris *et al.,* 2007a) prior to integration into the RCI (Healey *et al*., 2012). The resulting RCI scores are split into five classes: very good, good, moderate, poor and very poor. As the RCI is developed using existing datasets, the approach is limited by the lack of available state-wide, targeted data at the relevant scale to enable a high degree of confidence (Healey *et al*., 2012). The RCI products have not been assessed or validated in the field, and their use as a planning tool is limited to local and regional scales. Projects are underway to address some of the limitations of the RCI.

NOW has developed a standardised riparian vegetation extent layer for NSW, suitable for environmental monitoring, reporting and evaluation (Garlapati *et al.,* 2010). The data were generated using the existing NSW woody vegetation extent layer and a newly developed stream order layer. The extent of riparian vegetation within 30 m buffer zones around rivers with high stream orders (3 or greater) has been mapped. The derived vegetation extent grids (25 m resolution) provide almost complete coverage of NSW CMA's (11 out of 13).

NOW is also investigating various remote sensing approaches to mapping farm dams. A pilot study undertaken in the Parkes and Braidwood regions (Shaikh *et al*., 2011) led to the recommendation of a semi-automated method using object-based classification of high resolution digital aerial imagery (ADS40) complemented by time-series SPOT-5 imagery. Accurate baseline mapping of farm dams is required for determining compliance, water planning, and water balance modelling and assessing the impacts of climate change.

Victoria

Vegetation mapping

In Victoria, native vegetation is mapped according to Ecological Vegetation Classes (EVCs), of which there are ~300 state-wide. EVCs are also characterised by biogeographical region, and the combination of both is used to determine the bioregional conservation status (BCS). EVC benchmarks have been established so that vegetation condition at site scale can be assessed against a reference condition. The Department of Sustainability and Environment (DSE) have produced state-wide native vegetation maps at 1:100,000 scale and 1:25,000 in some areas (VIC DSE, 2007). The mapping includes pre-clearing (pre-1750) and extant (current EVCs) vegetation extent. The mapping approach relied on aerial photograph interpretation (API), environmental data (e.g., soils, rainfall and topography) and ground-truthing on a project-wide basis.

More recently, time-series Landsat imagery, ancillary datasets and ground truth were combined to model the spatial distribution of native vegetation extent. Revised maps of native vegetation extent and vegetation quality (based on the Habitat Hectares approach) have been produced for 2005 for the state (VIC DSE, 2007). The modelling will be repeated every 5 to 10 years.

The native vegetation extent map was produced by combining tree cover (derived from neural network, NN, classification of Landsat images from 1998-2005 and also SPOT data), grass cover (derived from NN modelling using field data, Landsat imagery and environmental data), water and plantations (derived from API, forest inventory and Landsat analysis) datasets. Model outputs represent 8 simplified classes, combining both cover type and probability score (e.g., Figure 8.5). The current dataset is limited by the scale at which it was produced, inclusion of areas of significantly altered native vegetation and poorly predicted vegetation, and lack of attribution on EVC and conservation status.

Modelled native vegetation quality maps (e.g., Figure 8.5) comprise data from a site condition model (75 % of the habitat score) which spatially predicts native vegetation condition from site-based assessments, and a patch-based landscape model (remaining 25 % of habitat score). The site condition model is based on NN modelling between sites of known vegetation condition and comprises input biophysical data (e.g., soil type, tree density), satellite imagery and climatic and topographic variables to predict native vegetation condition. The patch-based landscape model assigns a rating to native vegetation based on patch size, shape, landscape connectivity and proximity.

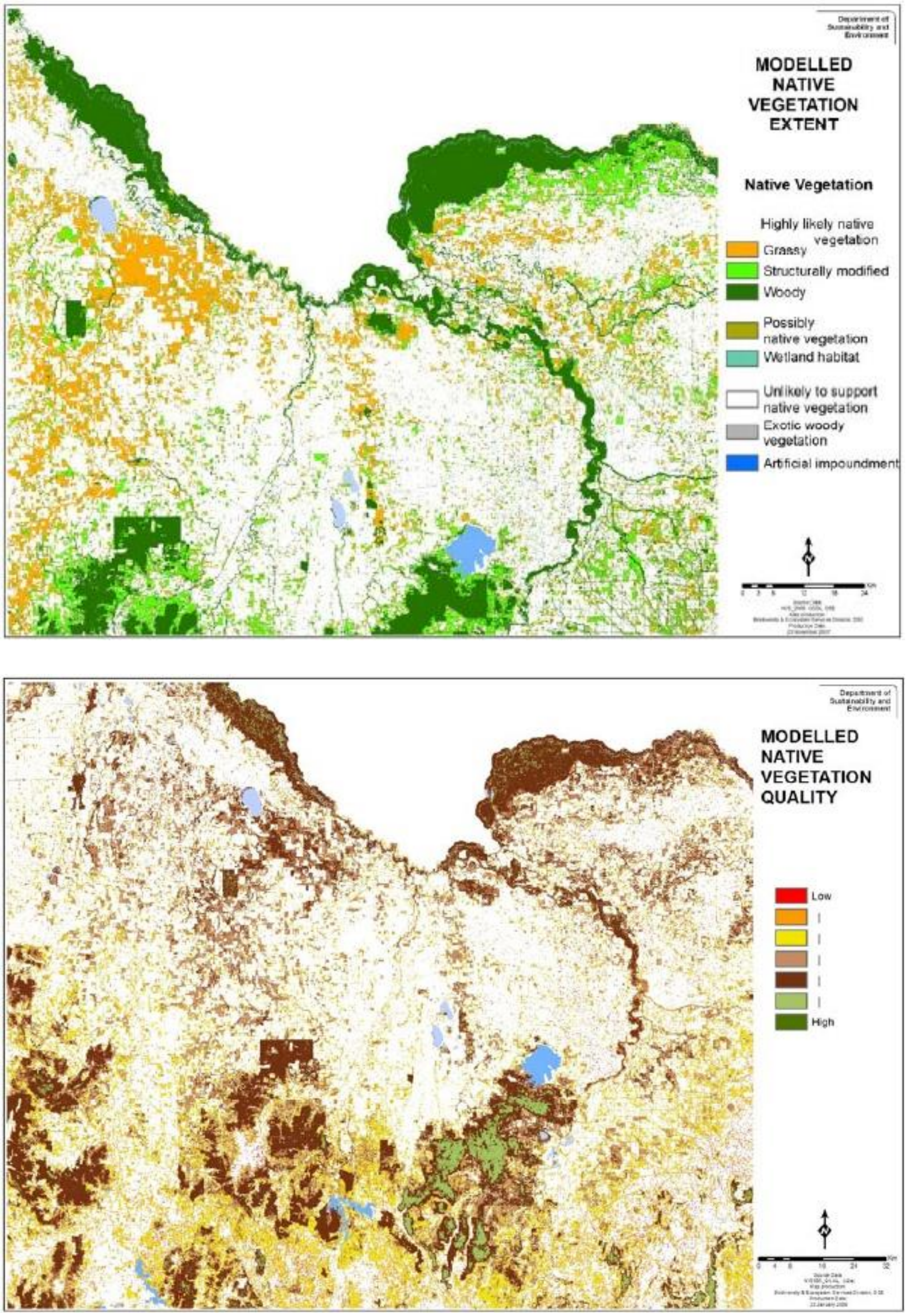


Figure 8.5 Sample data for modelled native vegetation extent (top) and native vegetation quality (VIC DSE, 2007).

A recent and extensive investment has been made in high resolution datasets to facilitate more detailed state-wide vegetation extent, EVC and condition mapping and stream condition assessment. Aerial photography and LiDAR have been captured over catchment areas, with RapidEye, SPOT and Landsat data available for the state. Model based EVC mapping at catchment scale will incorporate new spatial layers (e.g., fAPAR and LAI) derived for woody vegetation. A revised higher resolution vegetation type map derived from the State-wide Land Cover Project will soon be released.

Revised EVC datasets are now being created in Victoria using a cluster analysis based on a combination of modelling of fine-scale satellite imagery, modelled distribution of plant attributes derived from quadrat data, and a variety of environmental features datasets. This allows for more transparent methods, and more frequent and cost-effective updating to provide a consistent and contemporary view of Victoria's remaining native vegetation. There are several advantages to this approach:

- the EVC classification can be revised based on explicit analysis of both environmental and plant attribute data, to provide a more consistent and transparent Statewide view;
- EVCs can be more consistently mapped across Victoria, and can be more readily re-mapped when required;
- the influences of climate change on the nature and distribution of EVCs can be more actively considered; and
- a more dynamic and spatially-refined concept of EVCs enables their use in the more nuanced decision tools that are increasingly guiding management and investment decisions.

The pre-1750 EVC dataset will be combined with a new dataset on native vegetation extent which is currently underway based on a combination of sources and techniques:

- use of 5 m RapidEye, 10 m Spot, 30 m Landsat and 225 m MODIS[2] spectral imagery, and 50 m ALOS MODIS - Moderate Resolution Imaging Spectroradiometer; ALOS - Advanced Land Observing Satellite
- appropriate site-based training datasets, filters and analysis used to help categorise vegetation as either native or exotic (e.g. plantations, urban plantings, windbreaks etc.)
- Landsat and time-series MODIS imagery, and appropriate site-based training datasets are analysed to detect the likely presence of native grass-dominated areas (time-series data can show fluctuations in growth patterns due to seasonal or climate events, which help discriminate between native and exotic species)

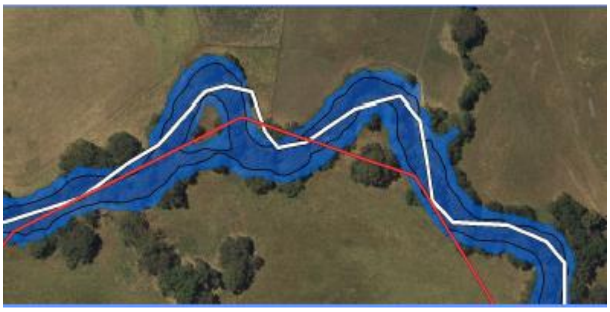
The EVC analysis will then use flora species presence / absence data available from more than 50,000 quadrats across Victoria analysed in combination with various environmental datasets to model distribution and classify. Current EVCs will be cut out of the pre-1750 dataset to produce current distribution and an updated EVC dataset. This is due for completion later in 2013.

Index of Stream Condition (ISC)

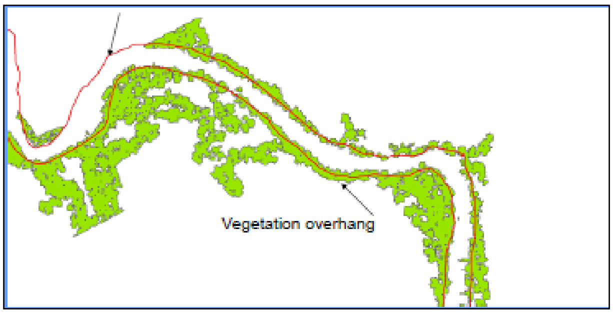
River condition in Victoria is assessed using the Index of Stream Condition (ISC; http://ics.water.vic.gov.au). State-wide assessments of stream condition have been undertaken in 1999, 2004 and 2010, with the next assessment scheduled for 2018 (DSE, Pers comm.). The ISC is a composite index of condition and comprises five components: hydrology, water quality, aquatic life, streamside zone and physical form, each of which is characterised by a suite of metrics. Previous assessments were undertaken by field crews and hence limited in scope. This changed in 2010 with the acquisition of LiDAR and aerial photography, which provided complete coverage along 28,000 km of river channels. The use of remote sensing provided a more accurate and comprehensive assessment of the status of rivers to inform the location and prioritisation of investment and on-ground works to improve river condition.

Aerial imagery is used to generate standard products, including DTM, slope, canopy height model (CHM) and fractional cover counts (FCC), and non-standard products, including the various metrics for streamside zone (e.g., vegetation width, fragmentation, vegetation overhang, large trees, tree and shrub cover and tree weeds) and physical form (e.g., bank condition and in stream large wood). The metrics for streamside zone are derived from LiDAR data, with the exception of tree weeds which are manually digitised from aerial photography. Bank condition is extracted from the LiDAR DTM, and in stream large wood is manually digitised from aerial photography. Future work will undertake the required field validation and review the process of delineating bank lines and individual tree crowns (VIC DSE, 2012).

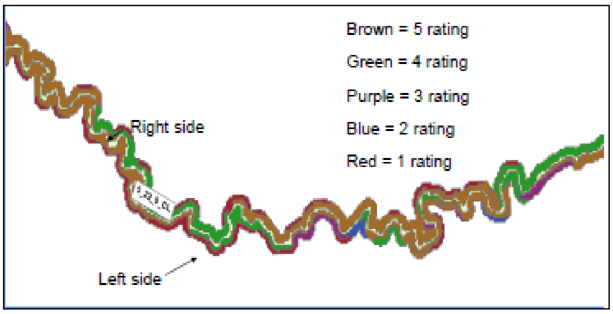
Importantly, the Victorian Index of Stream Condition Program is the largest operational demonstration of the use of LiDAR and aerial imagery to map and characterise riparian vegetation in Australia to date, and should be viewed as a benchmark for future programs in other jurisdictions. The images below provide examples of the ISC outputs derived from the LiDAR and aerial imagery (Figure 8.6).



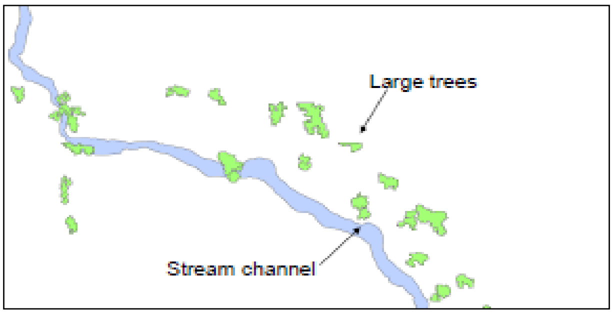
A) Comparison of previous mapping and ISC LiDAR derived water course.



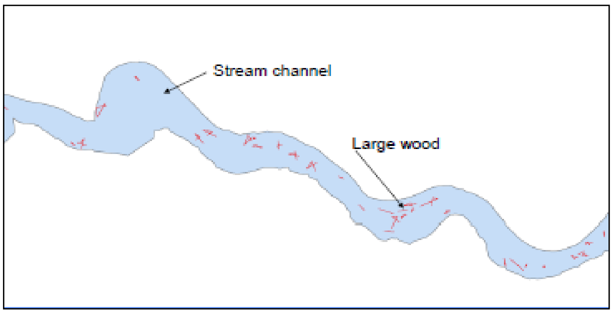
B) Vegetation overhang



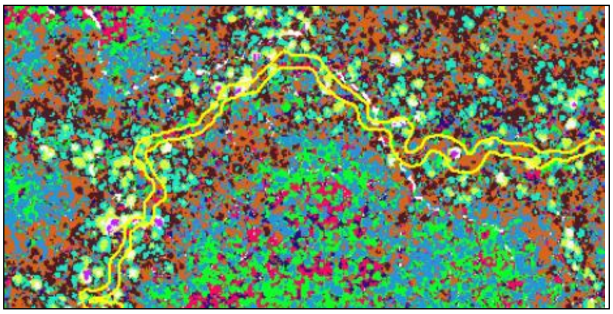
C) Structural variability



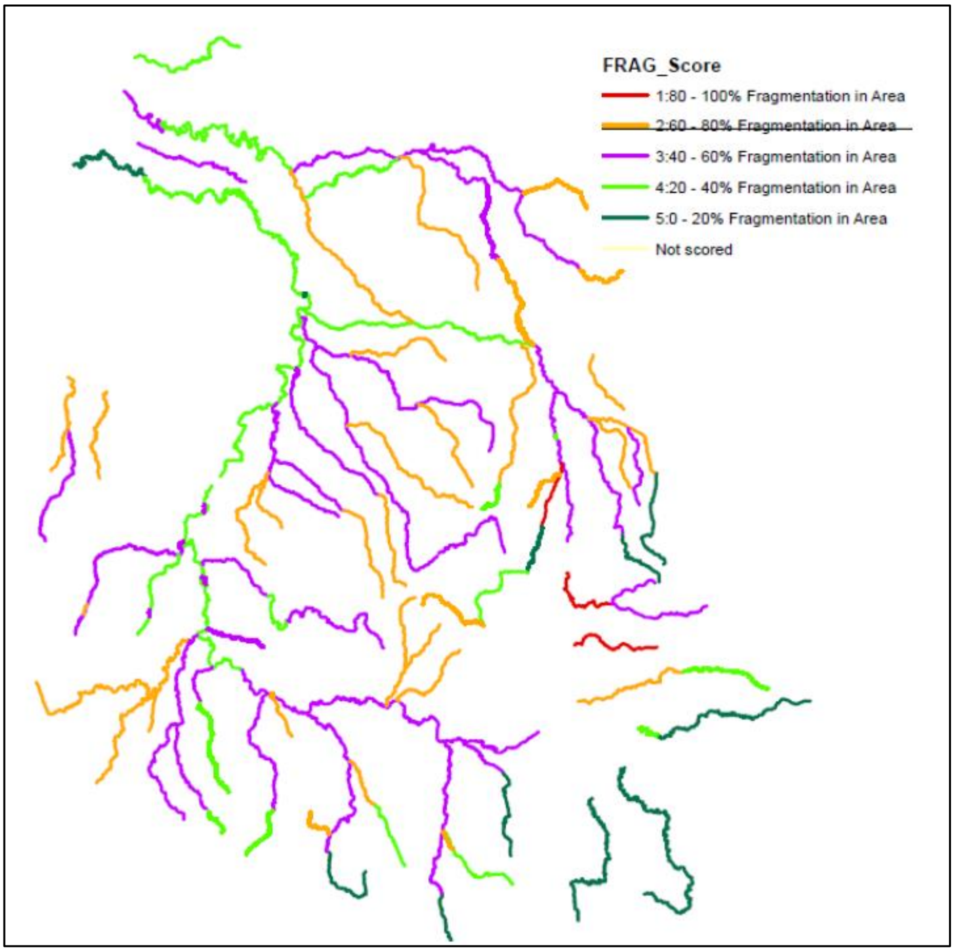
D) Large trees



E) Large Woody Debris



F) Canopy Height



G) Goulburn-Broken Catchment Riparian Fragmentation

Figure 8.6 Example outputs from the Index of Stream Condition program (DSE, 2102).

Irrigated crop water use

The Department of Primary Industries (DPI) is actively engaged in the development and application of satellite based methods for quantification of irrigated crop evapotranspiration (ET). The approach uses the METRIC implementation of the SEBAL algorithm (Allen *et al.,* 2007) to generate pixel-scale estimates of ET using satellite derived and meteorological (e.g., air temperature, wind speed, relative humidity and solar radiation) inputs. METRIC was designed for ET estimation in irrigated landscapes and takes into account the effects of surface topography on the radiation balance (Allen *et al.,* 2007). DPI has parameterised METRIC using inputs derived from Landsat data. Surface temperature, for example, was derived from thermal band 6, LAI was estimated from Landsat derived Surface Adjusted Vegetation Index (SAVI), and NDVI was calculated using Landsat bands 3 and 4 (Whitfield *et al.,* 2010).

DPI has demonstrated the capacity to quantify irrigated crop ET for the main crops/pastures in the major irrigation regions of the Murray Darling Basin using the METRIC algorithm (e.g., Figure 8.7; Whitfield *et al.,* 2010, 2011, 2012). The strong relationship between ET and NDVI was confirmed using Landat-5 imagery acquired in drought and post-drought years. Major sources of ET were identified within irrigation storages, riparian areas and irrigated horticulture. Seasonal and daily estimates of ET were derived from image and crop specific ET-NDVI relationships. The methods developed will facilitate more objective evaluations of the potential for improved water use at farm scale, and assess the regional impacts of sustainable diversion limits on perennial and annual cropping and environmental assets at catchment scale (Whitfield *et al.,* 2010).

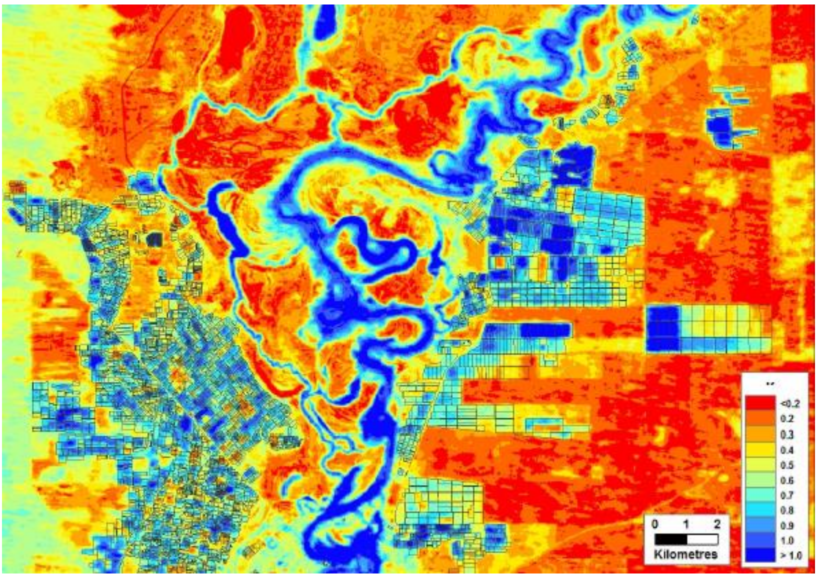


Figure 8.7 DPI SEBAL-METRIC Kc map, ET/ETR, of horticultural enterprises in the Renmark areas of the Riverland Irrigation District Victoria (Whitfield *et al.,* 2010).

Queensland

The Queensland Department of Environment and Resource Management (DERM) are actively engaged in the development and application of remote sensing technologies for state-wide vegetation and land use assessment. The majority of programs utilise time-series Landsat data with extensive field calibration and verification, and are closely aligned with policy formation and evaluation (Witte and Scarth, 2012). A number of operational monitoring programs are outlined below.

Statewide Landcover and Trees Study (SLATS)

SLATS (http://www.derm.qld.gov.au/slats/) is an extensive vegetation monitoring initiative of the QLD Department of Science, Information Technology, Innovation and the Arts (DSITIA). SLATS compiles spatial information on woody vegetation cover and change for vegetation management and compliance and greenhouse gas inventory (QLD DSITIA, 2012). Time-series Landsat TM and ETM+ imagery are used to compare vegetation cover from 1988 to 2010 at 1:100,000 scale, and for baseline mapping of land cover mapping for the whole State. The Landsat resolution (30 m) and consistent archive is appropriate for mapping woody vegetation change of 1 ha or greater, however, its use is limited for mapping riparian vegetation or small patches of remnant bushland that require higher resolution imagery (QLD DSITIA, 2012).

Continuous improvement of SLATS methodologies has greatly improved the capacity to accurately map woody vegetation extent and change. Much R&D has focussed on improving methods of image rectification (Gill *et al.,* 2010), field calibration and mapping of foliage projective cover (Lucas *et al.,* 2006; Armston *et al.,* 2009), and woody vegetation change detection (Kitchen *et al.,* 2010).

Foliage Projective Cover (FPC) is produced routinely for the State through modelled relationships between time-series Landsat-TM/ETM+ data and extensive field measurements of FPC and basal area (Figure 8.8). The FPC product is used in annual reporting of woody vegetation extent and loss of above-ground biomass (AGB) due to clearing (Figure 8.9). LiDAR data is used to validate model predictions of FPC and perform bias assessment (Armston *et al.,* 2009). The Landsat-FPC approach in QLD is being transferred to NSW. Woody vegetation change is modelled using past change rasters, time-series wooded extent and FPC index values for the entire Landsat archive. The accuracy of woody extent and change data is assessed by field verification and cross-validation with SPOT-5 imagery. The approach is limited by the low resolution (10 m) of the SPOT-5 data, and limited availability or lack or coincident and retrospective data (QLD DSITIA, 2012).

SLATS are also investigating the potential to detect long-term changes in vegetation cover such as regrowth, thinning and woody thickening. Methods will be developed that utilise the extensive Landsat archive to detect subtle change at sub-pixel level.

Future SLATS reporting is dependent on access to data acquired by the newly launched Landsat-8 LDCM. Gaps in the Landsat data record exist due largely to degrading electronic equipment (Landsats-5 and -7) and eventual failure of Landsat-5. Alternative data sources, including SPOT-4/-5 data, are a costly option.

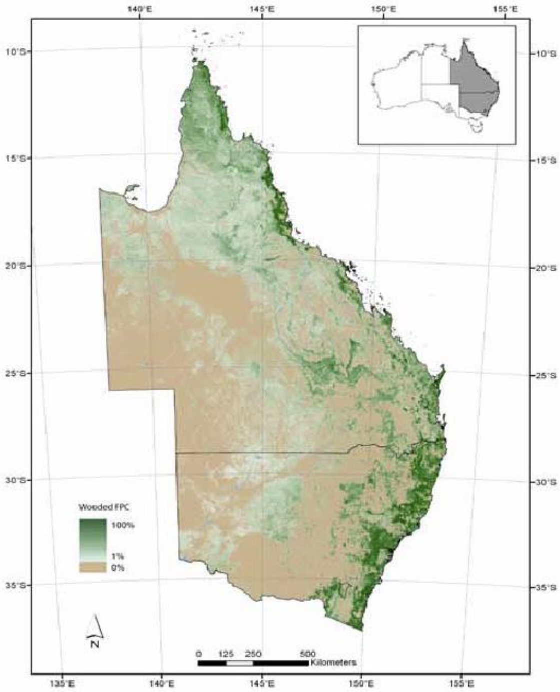


Figure 8.8 Percent Foliage Projective Cover (FPC) derived from time-series Landsat-5 TM and Landsat-7 ETM+ data for eastern Australia (JRSRP, 2011).

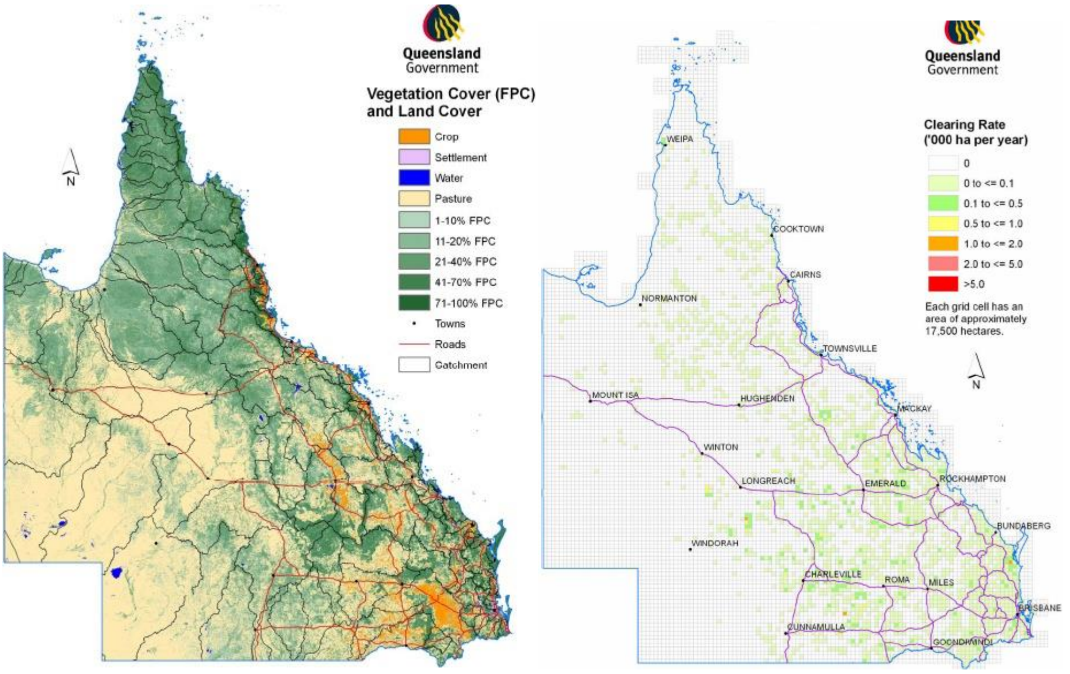


Figure 8.9 QLD SLATS vegetation mapping products: Wooded vegetation extent, FPC and land cover, 2009 (left), and average annual woody vegetation clearing rate, 2009-2010 (right; QLD DSITIA, 2012).

Ground cover monitoring

Operational ground cover monitoring is in place in QLD and NSW, with routine generation of fractional cover estimates using time-series Landsat imagery (Scarth *et al.,* 2010). Fractional cover mapping uses a constrained unmixing model with end members derived from field sampling (Witte and Scarth, 2012). The output image shows the percentage of bare, green and non-green (dead) fractions (e.g., Figure 8.10). The information is of use to land managers and governments involved in adaptive land management, fire and flood/erosion risk assessment, and assessing the impacts of climate change. Extensive field data was collected over 2000 – 2009 in grazing and croplands. The algorithm has been made available to Geoscience Australia, who will generate a national annual fractional cover product from 2013 onward.

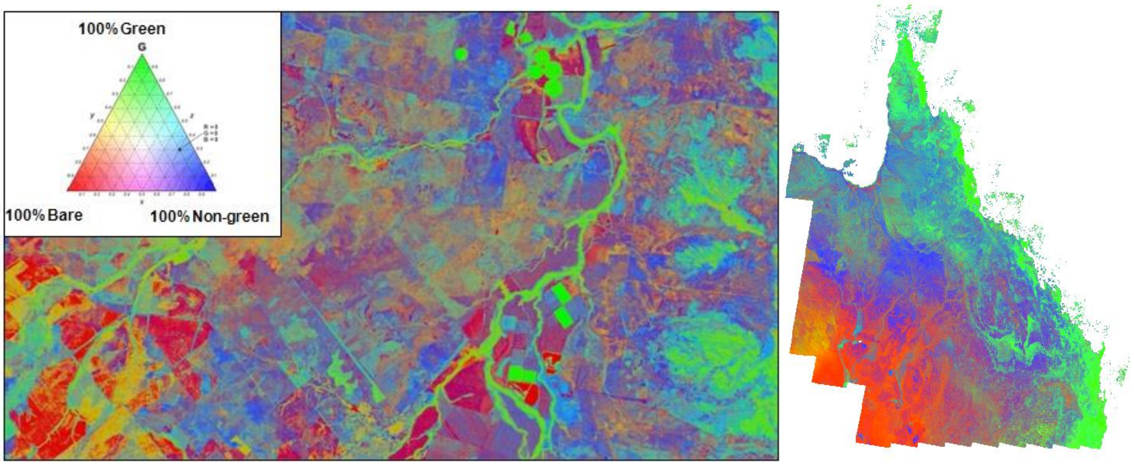


Figure 8.10 SLATS ground cover products: (Left) Landsat derived fractional cover for Emerald, QLD (bare, green and dead in RGB; Scarth *et al.,* 2010) and (Right) seasonal ground cover from 1986 – 2012 for QLD (Witte and Scarth, 2012).

Joint Remote Sensing Research Program (JRSRP)

The Joint Remote Sensing Research Program (JRSRP) is a collaborative program coordinated by the University of Queensland across remote sensing groups in Queensland, New South Wales and Victoria (http://www.gpem.uq.edu.au/jrsrp), charged with applied research to support environmental management at local, state and national scales. At the core of the program is the development of automated pre-processing routines and time-series algorithms for calibration and validation of biophysical map products.

More specifically, the JRSRP undertake research in:

- Atmospheric and topographic correction of satellite imagery (including full correction of 35 years of Landsat data collected every month over Australia; Gill *et al*. 2010; Gillingham *et al.* 2012, 2013; Flood *et al.* 2013).
- Development of automated methods for detecting cloud, cloud shadow, water bodies and burnt areas.
- Mapping annual and rapid vegetation change using SPOT-5 and Landsat data. The QLD DERM method of using time-series Landsat to data to generate Foliage Projective Cover (FPC) has been modified for use with NSW SPOT-5 data to provide information on vegetation cover and change at a higher resolution (JRSRP, 2011). SPOT-5 FPC could also be used as an alternative to woody/non-woody vegetation mapping in NSW (compared to current method).
- Mapping vegetation structure and biomass using imaging radar, including the development of radar correction and processing techniques for extraction of tree height, cover and biomass using ALOS PALSAR and Landsat data, in collaboration with JAXA and University of Aberystwyth (Clewley *et al.,* 2010, 2012).
- LiDAR validation of Landsat FPC maps. Landsat-derived FPC is used by NSW OEH to map woody vegetation extent and change. The majority of calibration data used to create these maps is based on site measurements taken in Queensland, and so a method to validate NSW products is required (JRSRP, 2011). An approach is under development that uses a combination of field measurements, high spatial resolution imagery and LiDAR data. Open source software (SPDLib; www.spdlib.org) for processing of LiDAR data was developed in collaboration with the University of Aberystwyth.
- Characterisation of riparian vegetation using LiDAR and high resolution imagery (Arroyo *et al*. 2010; Johansen *et al.* 2010).

Regional Ecosystems (RE) mapping

The QLD Herbarium has developed a method for mapping regional ecosystems (RE) in QLD (http://www.ehp.qld.gov.au/ecosystems/biodiversity/re_introduction.html). The RE classification is based on vegetation communities in a bioregion that are consistently associated with a particular combination of geology, landform and soil (Sattler and Williams, 1999). A hierarchical classification scheme is applied, wherein the land is classified by bioregion, land zone and then vegetation (association) or associated variation in geology/landforms/soils within a land zone (Neldner *et al.,* 2012). A fourth class is added for vegetation communities or proposed new REs. REs and vegetation associations are typically mapped at 1:100,000 scale.

The two main mapping products developed are current remnant and pre-clearing RE's and vegetation (Neldner *et al.,* 2012). Pre-clearing maps are derived from interpretation and manual digitising of historic aerial photographs (black and white photos available from 1960's) and additional data layers. Remnant extent mapping relies largely on interpretation of Landsat TM imagery, some SPOT imagery and aerial photography, and ground truth. Remnant/non-remnant status is determined by comparison with reference sites established in the field or from published benchmarks. The mapping is updated every two years.

Riparian vegetation mapping

Landsat based methods have been developed for mapping and monitoring riparian forest and ground cover in the QLD Murray Darling Basin and Bulloo catchments (Figure 8.11; Clark and Healy, 2012). The need for higher resolution data, such as that acquired by SPOT-5 is recognised.

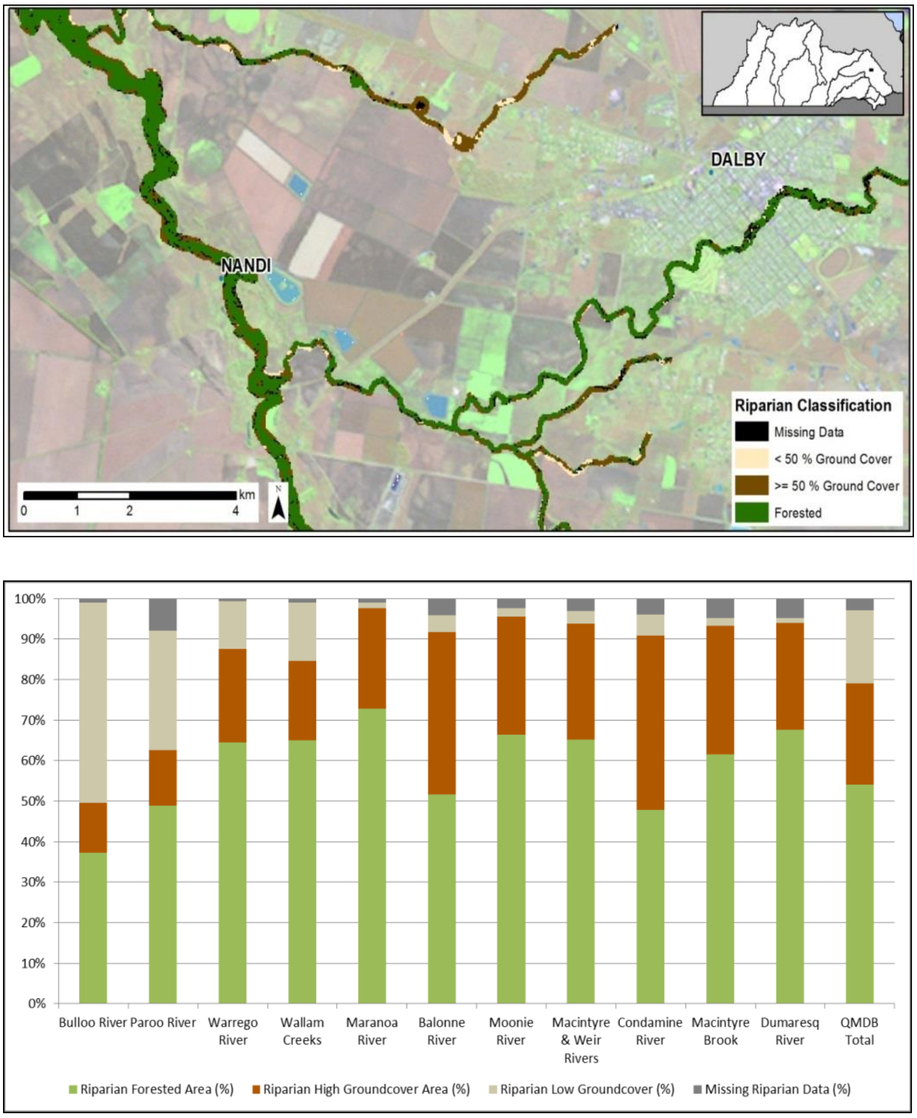


Figure 8.11 QLD Riparian vegetation mapping (Clark and Healy, 2012).

QLD Land Use Mapping Program (QLUMP)

The QLD Land Use Mapping Program (QLUMP; http://www.derm.qld.gov.au/science/lump/) maps and monitors land use and land use change across the State in accordance with the Australian Collaborative Land Use Mapping Program (ACLUMP) and guidelines for national land use classification (the Australian Land Use and Management, ALUM, classification; ABARES, 2011). Land use information supports a variety of applications including sustainable management of QLD's natural resources, environmental protection, urban planning and agricultural production.

A state-wide land use map is available for 1999, and land use datasets are available for selected catchments in 2004, 2006 (e.g., QLD Murray Darling Basin, Figure 8.12) and 2009. Coastal zones and high intensity land use areas are mapped at 1:50,000 scale, while the pastoral zone and low intensity land use areas are mapped at 1:100,000 scale. Catchment scale mapping combines state cadastre, public land databases, satellite data, ancillary land cover/land use data and field survey (ABARES, 2011). Satellite data are sourced from a range of sensors including aerial photography, Landsat TM/ETM+, SPOT-5 and Quickbird. Land use classes are verified using field data and expert knowledge. Mapping accuracy is assessed using independent points sourced from field survey or large-scale aerial photography. Land use change is assessed by comparing the previous land use datasets with new datasets to identify areas that have changed (ABARES, 2011). The 1999 baseline land use map for QLD provides the basis for monitoring land use change.

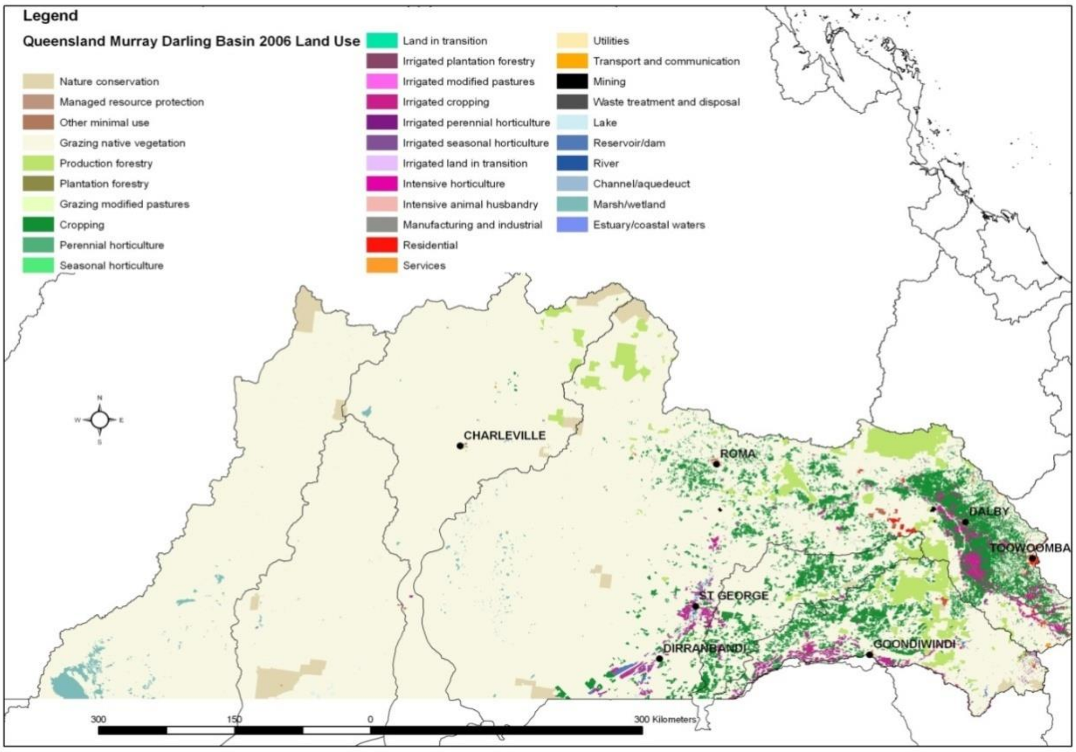


Figure 8.12 Land use mapping in the QLD Murray Darling Basin for 2006 (Witte and Scarth, 2012).

Crop monitoring

QLD are also developing methods for crop frequency monitoring using time-series Landsat and ALOS PALSAR data from 2000 – 2011. An object-oriented approach based on time-series segmentation of Landsat green reflectance and PALSAR HH and HV backscatter is being investigated (Witte and Scarth, 2012). A series of landscape objects will be output from the segmentation process. Vegetation structure will be assessed within the objects (including height, mid-storey and age class). The change in persistent green between objects will be estimated, indicative of trends and responses to management and climate. Change in the distribution of bare ground between objects will be used to evaluate erosion and land condition over time.

Water body extent and persistence mapping

Water bodies in QLD were mapped using time-series Landsat-5/-7 data acquired between 1987 and 2009 (DERM, 2010). The classification scheme was based on thresholding a standardised multiple regression water index. The outputs from each year were combined to produce a mean extent layer for all years. The number of years that water was present in each water body has been calculated, together with a percent value indicative of persistence. Some polygons have been attributed with the name, primary use and owners of dams where point data was available from the Dam Safety database. Only dams larger than 1875 m^2 (approximately three Landsat pixels) have been mapped. Smaller dams may be mapped in a future project.

Wetland mapping program

The QLD Wetlands Program undertakes state-wide wetland mapping using existing information (Landsat derived water bodies), RE mapping, topographic data and a springs database (EPA, 2005). Higher resolution data (SPOT and aerial photographs) and ancillary datasets (geology, soil and land system mapping) are used to attribute and assess the derived wetlands mapping products. Current wetland extent mapping for 2009 is available at a scale of 1:50,000 in coastal areas and 1:100,000 in inland areas. Mapping will be updated every four years using satellite imagery. As additional information becomes available through field survey, improved methodologies for water body mapping, and updates to drainage mapping, the product will be improved.

South Australia

The South Australia Department of Environment, Water and Natural Resources (DEWNR) is involved in the design and implementation of operational monitoring programs and policies for management of the State's natural resources. Information is gathered by means of field survey, national census, public consultation existing mapping and remote sensing.

Regional native vegetation extent mapping focuses on current and pre-European vegetation extent. Areas greater than 0.5 ha are mapped by ground survey and interpretation of aerial photography and satellite imagery (Landsat TM). There is limited condition assessment at present. Vegetation is described and mapped according to the National Vegetation Information System (NVIS). Polygons are attributed with extent, vegetation type, structure, dominant species and stratum characteristics. Floristic mapping of remnant native vegetation is currently available for around 50 % of the State (DEH, 2006). Pre-European mapping is ongoing and currently only available for a few areas.

Mangrove and saltmarsh communities have been systematically mapped across South Australia. The data provide useful information on the extent of estuaries, type and size of habitats, and are used to determine conservation status. Wetland inventories are mostly undertaken at regional scale, and are field-based studies, augmented by aerial photography, topographic mapping and satellite imagery. Management plans have been developed for the six RAMSAR wetland sites in SA, with detailed habitat mapping at some of these sites. The Coorong and Lower Lakes were mapped in two stages between 2002 and 2003 (Seaman, 2003). Habitat mapping was undertaking at 1:50,000 scale through the integration of existing GIS layers and survey data (e.g., vegetation mapping, topography, soils, land tenure, mapped distributions of aquatic fauna), and verified by interpretation of aerial photography. Gaps in habitat coverage were completed by on-screen digitising of aerial photography and streaming GPS surveys. Classified habitats were attributed with field observations relating to habitat form and condition. Sample high resolution habitat mapping products for Coorong Lakes are provided in Figures 8.13 and 8.14 (DEWNR, 2012).

a) Zone 1 -ploughed substrate. Zone 2 -weed/substrate. Zone 3 –couch. Zone 4 –substrate bank. Zone 5 –water. Zone 6 –reed. Zone 7 –couch. Zone 8 –samphire /substrate.

b) Zone 1 –weed. Zone 2 –couch/weed. Zone 3 –water. Zone 4 –couch/weed. Zone 5 – samphire /weed. Zone 6 –unknown. Zone 7- substrate/weed. Zone 8 –couch/weed. Zone 9 –reed. Zone 10 –couch/weed.

c) Zone 1-reed. Zone 2- couch/weed. Zone 3 –samphire /pasture Zone 4- pasture/weed.

Figure 8.13 Sample transects and detailed habitat classification for Coorong Lakes (DEWNR, 2012).

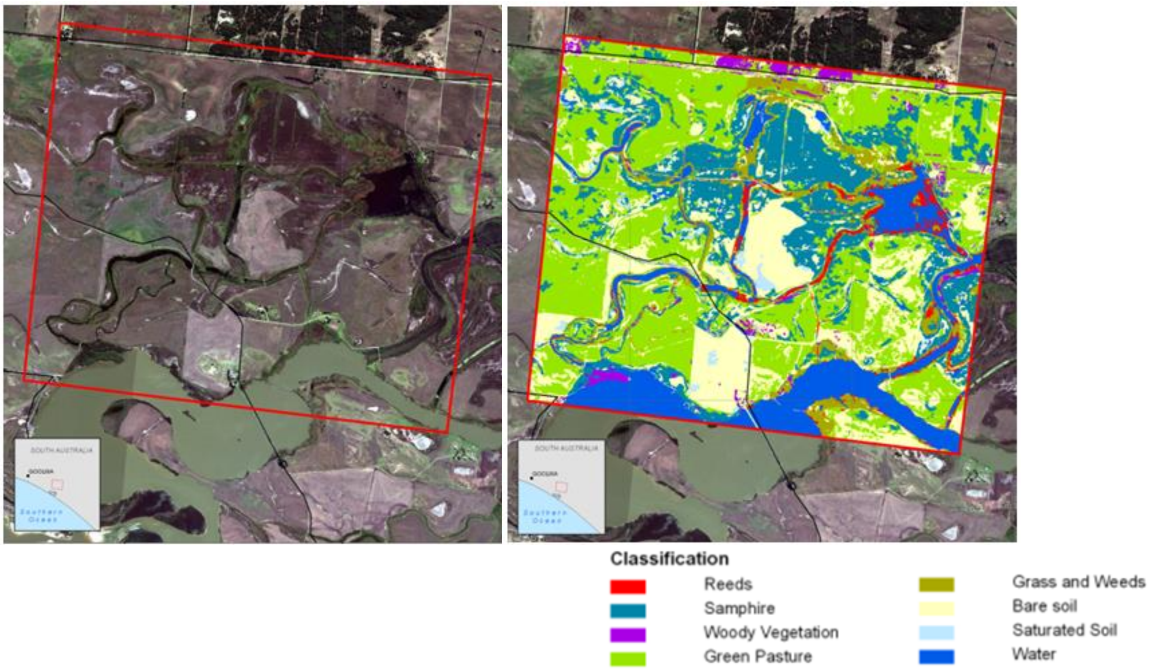


Figure 8.14 High resolution aerial photography and detailed habitat classification for Coorong Lakes (DEWNR, 2012).

National Initiatives

A number of national initiatives are underway of relevance to MDBA business and spatial information needs, either through provision of data and standard products, operational methods and/or expert networks.

TERN/AusCover

The AusCover facility (http://data.auscover.org.au/) provides a national expert network and data delivery service for a range of Australian biophysical time-series products and selected high resolution datasets over TERN sites (Figure 8.15). Coordinated by CSIRO, AusCover supports a nationally consistent approach to delivery and calibration and validation (cal/val) of existing and future satellite-derived datasets. Standardised biophysical products will be made available through a Distributed Data Archive and Access Capability (DAAC), with several regional nodes for production and quality control. A web portal is being developed for visualisation of spatial data available in the TERN/AusCover facility. There is ongoing development of technical documentation such as AusCover Good Practice Guidelines on cal/val of remotely sensed data products and field protocols.

The types of data that are currently or will be made available include land cover (e.g., fractional cover, persistent green vegetation fraction, forest cover), ecosystem variables (e.g., gross primary productivity, phenology, disturbance index), vegetation indices (e.g., NDVI, EVI, LAI and fAPAR), fire products (e.g., burnt area, fire frequency and fire severity), radiation, meteorology and ancillary (e.g., daily precipitation, air temperature and water vapour pressure), base satellite data (e.g., MODIS BRDF adjusted, surface and top of atmosphere reflectance), site-based datasets (e.g., terrestrial and airborne LiDAR, airborne hyperspectral and ground calibration data, sunphotometer measurements, and hemispherical photography) and atmospheric products (e.g., MODIS aerosol, water vapour and cloud mask).

Development of the AusCover mobile data collection and crowd-sourcing application (Geo-wiki) is almost complete (McVicar *et al*., 2012). Users will soon be able to collect (and share in real time) field data for cal/val of land cover/land use products using mobile devices. The data will be hosted in real time either in the Google Cloud or transferred directly to the AusCover database.

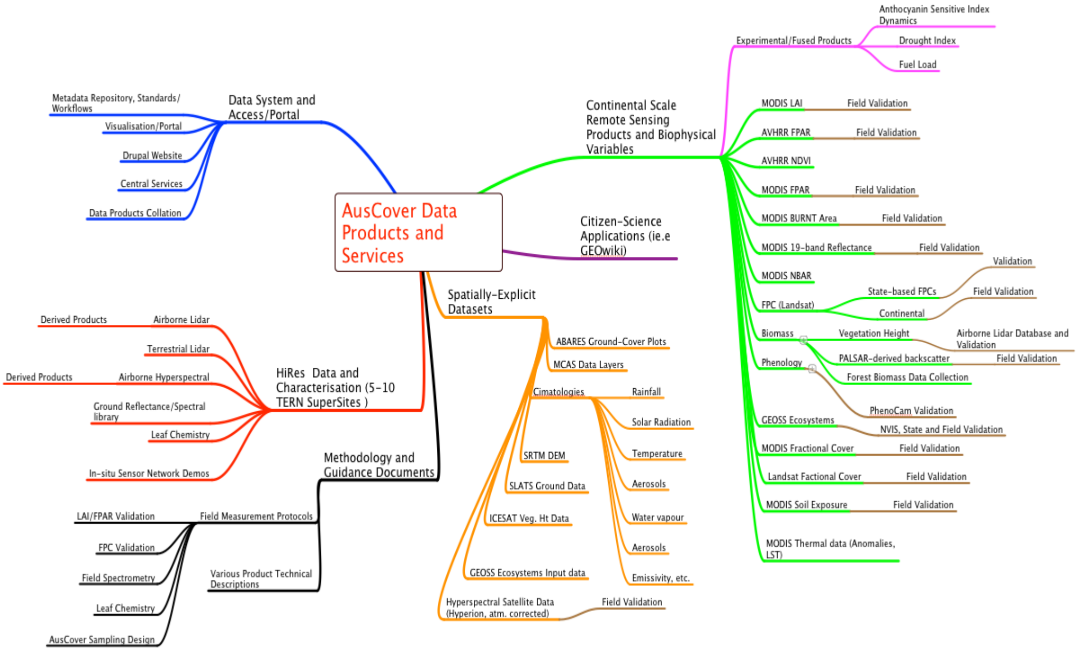


Figure 8.15 Flowchart describing AusCover data products and services (McVicar *et al*., 2012).

The National Dynamic Land Cover Mapping project

Geoscience Australia (GA) and the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) have developed a Dynamic Land Cover Dataset (DLCD) for Australia (Lymburner *et al.*, 2011; http://www.ga.gov.au/earth-observation/landcover.html). The DLCD is based on time-series MODIS extracted Enhanced Vegetation Index (EVI) over the period 2000 - 2008. MODIS time-series signatures for each pixel were reduced into 12 coefficients based on statistical, phenological and seasonal characteristics, and subsequently clustered and labelled based on class names from catchment scale land use mapping and the NVIS (Figure 8.16; Lymburner *et al.*, 2011). The method is transferrable to other satellite datasets. The data are useful for assessing change in land cover dynamics in forested and non-forested ecosystems in response to natural and human induced change. The accuracy of derived land cover classes has been assessed using an extensive set of field site data available from various State agencies.

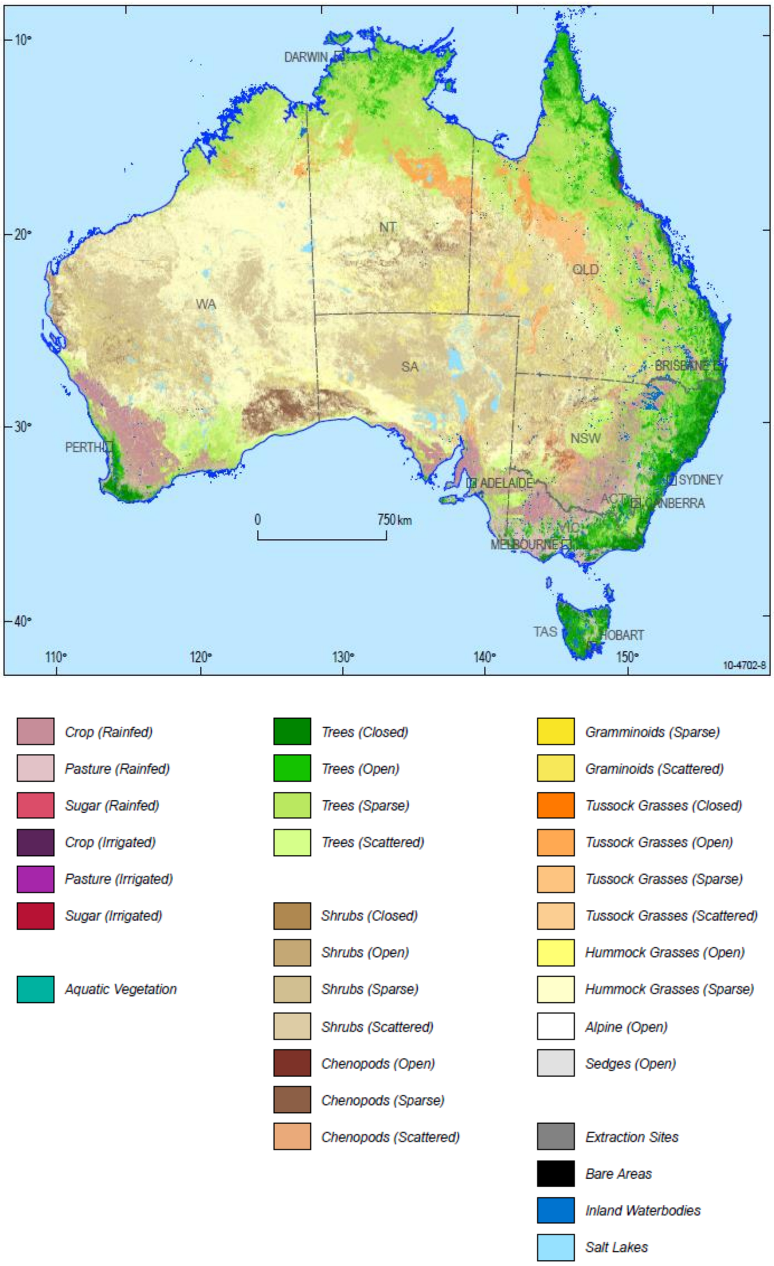


Figure 8.16 Sample map derived from the National Dynamic Land Cover Dataset (DLCD) for 2000 - 2008 (Lymburner *et al.*, 2011).

National Carbon Accounting System (NCAS)

Australia's National Carbon Accounting System (NCAS) was established by the Australian Greenhouse Office (now Department of Climate Change and Energy Efficiency) in the early 2000s, and was one of the first to produce a national operational carbon accounting system based on satellite imagery (AGO, 2002; *Furby et al.,* 2008). NCAS is composed of a series of country-wide forest extent, land cover/land use and change maps at 25 m resolution from 1972 to present generated through time-series processing of the Landsat archive. These data, in conjunction with meteorological data, soil type and carbon and land management information are combined in the Full Carbon Accounting Model (FullCAM) to estimate greenhouse emissions arising from anthropogenic activity. The outputs support national reporting requirements for the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol Greenhouse Gas Inventory.

New products are being developed using the available calibrated archive. National Forest Trend (NFT) information, representing within-forest changes over time has been produced at 25 m spatial resolution for the Australian continent (Figure 8.17; Lehmann *et al.,* 2012). The NFT is based on time-series extracted woodiness index, from which statistical trend summaries are calculated, and displayed as coloured maps representing the approximate timing, direction, magnitude and spatial extent of changes in vegetation cover. Compared to NCAS forest cover extent and change maps, more subtle changes in forest density are detected in NFT datasets. The NFT data identify disturbances in forest cover that may not have resulted in a change in land use.

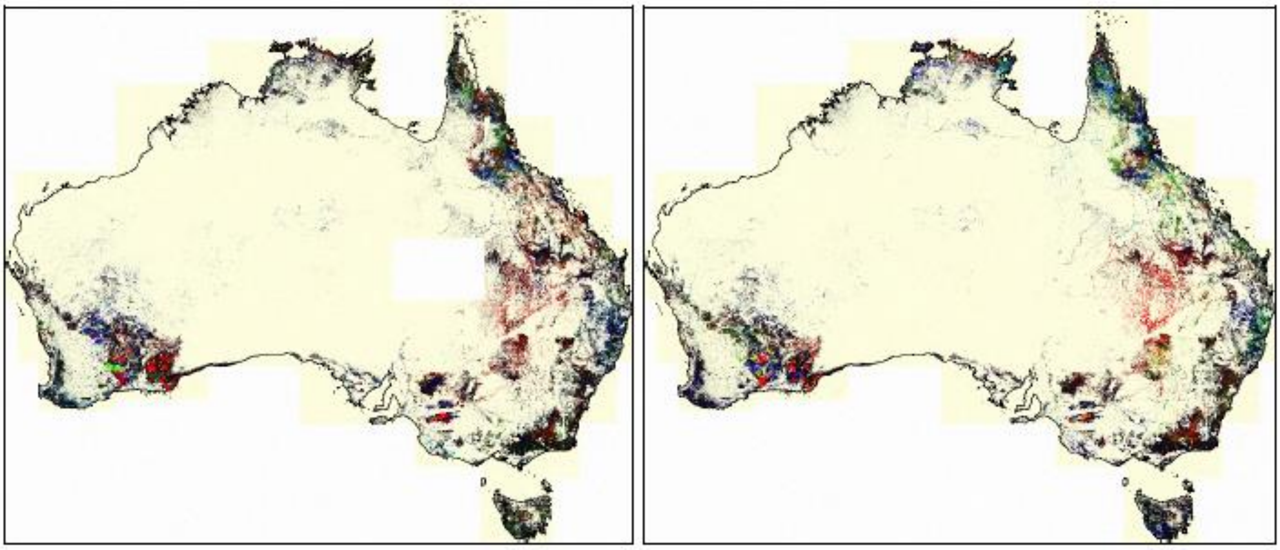


Figure 8.17 Australia-wide National Forest Trend (NFT) information for 1989 - 2006 (left) and 2000 - 2006 (right) derived from time-series Landsat derived woodiness index (Lehmann *et al.,* 2012).

Australian Water Resources Assessment (AWRA)

The Australian Water Resources Assessments (AWRA), available from 2010, outlines the trends and variability in water use at regional to national scales (http://www.bom.gov.au/water/awra/index.shtml). This information is required for reporting on the status of Australia's water resources under the Water Act 2007. The AWRA system was developed by CSIRO and the Bureau of Meteorology (BOM). Modelling of water storages and flows in vegetation, soil and groundwater systems is performed using the AWRA-L biophysical model (Van Dijk, 2010). Daily water balance estimates are produced at ~ 5 km resolution with input from ground and satellite-based observations. Continuous improvement of the system is underway with the integration of models for other water cycle components and incorporation of newly acquired ground and satellite observations.

Potential Collaborative Opportunities

One of the greatest challenges facing the MDBA is engaging other Federal and State agencies, CMAs and local stakeholders to foster a collaborative environment for sharing data and knowledge relating to the sustainable management and wise use of the MDB. The cooperation of the various interest groups is paramount in ensuring the protection, maintenance and restoration of the basin's biophysical resources now and into the future. Given the demonstrated benefits of geospatial data to contribute to monitoring, evaluating and reporting on basin assets, there is an urgent need to secure ongoing access to data and information products through coordinated co-investment, and partnerships for developing and implementing long-term operational programs that meet the critical business and information needs of the MDBA and others through mutually beneficial partnerships.

Opportunities exist for more structured and shared data acquisition and potential collaboration between the States and MDBA. State capabilities to map key environmental and socio economic variables could be leveraged through channelling of funds towards purchase of data to fill gaps in coverage or where high resolution data is a requirement; the main driver being the generation of consistent, robust biophysical products that support state-and basin-wide operations.

The current lack of communication between the States in terms of their vegetation survey and mapping programs means that there are major inconsistencies in vegetation classification across State/Territory boundaries (Benson, 2006). Limited funds are available for future monitoring programs and optimally, funds and expertise should be pooled in the national interest. Initiatives such as TERN/AusCover and AEOCG that promote data sharing and consistency in field and remote sensing based calibration and validation are demonstrating the benefits of collaboration.

Both NSW and VIC have made considerable investment in high resolution imagery for state-wide mapping of native and riparian vegetation (e.g., NSW SPOT-5 program, VIC DSE LiDAR-ISC program). The use of aerial photography features heavily in NSW, VIC and SA vegetation monitoring programs. QLD, on the other hand, has focussed on harnessing the potential of the unlocked Landsat archive for long-term biophysical monitoring (e.g., SLATS), but are also using SPOT5 extensively through NRM regional bodies. Considerable research effort has led to routine production of Foliage Projective Cover (FPC) and fractional cover for the State, useful for monitoring changes in woody vegetation extent and ground cover. Standard routines are available for pre-processing imagery and producing consistent, state-wide mosaics.

Time-series Landsat FPC is available for QLD, NSW and VIC and could be expanded to SA, providing basin-wide coverage of woody vegetation extent using a standardised, established method that has been validated. The same could be implemented for ground cover. Additional investment in high resolution LiDAR and SPOT-5 data for the remaining States could see the development of a consistent, basin-wide vegetation extent and type map, riparian vegetation map, and a high resolution DEM for topographic and flow modelling. The integration of these data would also support methodology development for vegetation condition assessment, which is considered by many as still in its infancy.

There is currently a paradigm shift towards how we view, access, share and use of remotely sensed data. The value of remotely sensed data in decision support systems and in effecting policy is increasingly recognised. International initiatives that promote shared access to data, open source software tools and user friendly web portals for dissemination of data and information are becoming increasingly common. The potential of pixel-level time-series data mining and bulk processing is being unlocked as extensive archives are made available. There is greater consideration of best practice vs. operational methods by the States in terms of meeting the needs of biophysical monitoring and reporting.

Greater engagement and dialogue is needed between basin users and stakeholders to ensure that the region's natural resources are not compromised to a state beyond repair. Increased knowledge is the key to success and there are numerous ways in which the States and MDBA can work together and contribute to this end.

9. KEY FINDINGS

There is clearly significant potential for remote sensing and related technologies to play a greater role in the Murray Darling Basin Authority's operations, and in many cases, to provide a more cost-effective, efficient and transparent means of achieving specific agency business and information needs. Importantly, there is no single solution. Information is required at a range of spatial and temporal scales, and requires a commitment to a suite of technologies, ICT infrastructures, methods, skills and knowledge (i.e. people) to take full advantage of available opportunities.

The review and synthesis has identified the following key findings in relation to the use of remote sensing to contribute to the business and information needs of the Murray Darling Basin Authority.

1 - For the potential of remote sensing to be fully realised its use must be placed within the broader context of a whole-of-basin monitoring plan, and adaptive management system.

The monitoring system should form an explicit component of the authorities adaptive management approach and be based on a sound: conceptual model of the Basin; overarching system design, and the principles outlined in Chapter 5 of this document. These principles include: a long-term commitment; clearly defined outcomes, goals, objectives and questions which link the strategic and tactical requirements of the target audiences.

2 – There are significant opportunities for existing state and national programs to address MDBA business needs.

There are a number of existing programs which have the potential to contribute directly to the MDBA's business needs. In particular, these programs include: QLD, NSW, VIC and SA high resolution imagery and LiDAR acquisition programs; National Carbon Accounting System (NCAS), the QLD and NSW SLATS and ground cover programs; NSW and VIC vegetation mapping programs; the VIC Index of Stream Condition Program; the Australian Water Resources Assessment Program; the VIC DPI irrigated crop water use program; TERN AusCOVER; The Dynamic Land Cover Mapping Project and the Unlocking the Landsat Archive initiative.

Significant opportunities therefore exist for formally coordinated, joint investment in high resolution data acquisition; collaborative processing of time-series data and tailored information products; investment in computing infrastructure and development of on-line processing and reporting capabilities; development of consistent vegetation type, extent and condition mapping across state borders, and ongoing applied research.

3 – There are a number of existing methodologies and datasets that could be extended to produce consistent remotely sensed products across the Basin.

There are several areas, where for a relatively small investment; the coverage of existing metrics could be extended to provide a consistent product across the basin. Some examples include: baseline riparian and floodplain vegetation type and extent, Woody vegetation extent and density at the scale of individual canopies, and the distribution of water harvesting and storage structures, industries and plants.

4 – Long term commercial service level agreements may offer more cost-effective and efficient mechanisms for acquiring and processing data related to specific events within the basin.

If information on the extent, timing and duration of flooding from environmental flows is seen as critical, tasking abilities offered by numerous commercial optical and SAR providers are necessary. Using either very high resolution satellite optical or SAR platforms, daily acquisitions are possible, and in key areas airborne platforms can acquire data on demand. By setting up service level agreements to acquire data over known area (e.g. Icon sites) at short notice, individual events may be monitored at high temporal frequency, allowing for more accurate assessment of the delivery and success of the event.

5 – Rapidly emerging capabilities require an ongoing commitment to applied research and development to realise the full potential of remote sensing in relation to MDBA business and information needs.

Several areas have been identified within this report, where further applied research and image acquisition is required before remote sensing technology can fulfil the needs of the MDBA. This may include the establishment of case studies to test new and emerging remote sensing technology, the development of new metrics analysed across the full time-series of available optical data, and the establishment of long term ground reference sites to strengthen ground truthing of existing products. The incorporation of on ground probes with loggers may also improve the remote recording of factors such as floodplain soil moisture.

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APPENDIX A. **BUSINESS AND INFORMATION NEEDS OF THE MDBA**

Table 3.1 MDBA business and Information needs by theme.

Information need	Justification	Spatial scale of consideration					Temporal scale of consideration		
		Site/reach	Asset	Floodplain	Valley	Basin	Event	Seasonal	Annual
Physical Form									
Accurate prediction of flow/inundation relationships along the River Murray and floodplains.	An understanding of the morphology of the floodplains and flow paths needed to provide reliable prediction of inundation extent and duration over floodplains and easements. Flow models need to transparently identify natural vs. managed flows, improving accountability and limiting liability.	X	X	X	X		X	X	X
Water Quality									
Water quality in the rivers and floodplains of the Basin.	Monitoring of water quality in Murray Darling Basin system in relation to both ecosystem outcomes (e.g. pH, DO, Salinity) and human health (Salinity, Algae) outlined in BP targets				X		X	X	
Mapping of algae/blackwater events.	Accurate maps of algae outbreaks and blackwater events to more effectively communicate with the community. Identification of source/sink areas in catchments to focus future management actions			X	X		X		
Catchment salinity monitoring.	Though primarily a role for the states there is a requirement for the MDBA to monitor aspects of salinity that the states aren't measuring - such as floodplain salinity accumulations.				X			X	X
Aquatic Biota									
Past and present ecological condition and response of fish/bird/vegetation at key environmental assets and between icon sites	Assessing the ecological benefits of watering and works and measures that have been introduced in the icon sites as part of TLM program, and more broadly for the assessment of the Basin Plan. Also required for River Murray Channel Water Management Plan and Environmental Watering Plan development. (*One of the inputs is vegetation*	X	X				X	X	

	extent, type and condition)								
Information need	**Justification**	**Spatial scale of consideration**					**Temporal scale of consideration**		
		Site/reach	Asset	Floodplain	Valley	Basin	Event	Seasonal	Annual
Predicting, planning and evaluating the ecological response to environmental watering.	Improved modelling of the ecological benefits of environmental watering using the Murray Flow Assessment Tool (MFAT). (*One of the inputs is vegetation extent, type and condition*)	X	X	X			X	X	
Hydrological Disturbance									
Estimation of floodplain harvesting and losses from ET	For compliance, accounting and flow/inundation modelling purposes.	X	X	X	X		X	X	X
Improved characterization of Ground-surface water connectivity	Improved understanding of ground-surface water connectivity would provide more reliable estimation of recharge, underground connections and aquifer storage.				X	X		X	X
Monitoring of groundwater levels and use outside of currently monitored areas.	Groundwater levels, abstraction and use are not currently monitored in many areas.				X	X		X	X
Catchment Disturbance									
Land Cover, Land-use and Land Management.	Assessing baselines, trends and potential changes in land cover, land use and land management data as inputs into hydrological models. Assessing changes in the patterns of land use, and particularly plantation development in a changing climate to assist with the longer-term development of water sharing plans				X	X			X
Vegetation extent, type and condition to inform changes in interception and fire risk associated with water reform.	Climate change and changes to land and water management may influence vegetation dynamics and hence catchment water interception and bushfire risk.				X	X			X
Mapping of Vegetation extent, type and condition to inform groundwater models	Need for a Basin wide annual vegetation map to allow for more accurate assessment of groundwater recharge/discharge over time to strengthen WAVES groundwater model					X			X

Information need	Justification	Spatial scale of consideration					Temporal scale of consideration		
		Site/reach	Asset	Floodplain	Valley	Basin	Event	Seasonal	Annual
Socio-economic									
Changes in irrigated and non-irrigated cropping over time for: Basin wide estimation of irrigation water use	Information on broad scale changes in irrigation water use will be required to assess the impact of water reform in the basin.				X	X			X
Changes in irrigated and non-irrigated cropping over time for: Assessing and predicting the impacts of the Basin Plan on the seasonal and annual cropping systems.	Changes to the seasonal and annual patterns of cropping across the basin could influence basin communities. Information addressing this will be required to assess and potentially predict these changes.					X			X
Changes in irrigated and non-irrigated cropping over time for: Assessing and predicting seasonal changes in cropping and changing socio-economics at the valley scale	How the distribution of cropping types within valleys, and hoe they may change as a result of the basin plan, could have socio-economic implications at the valley scale.				X			X	
Changes in irrigated and non-irrigated cropping over time for: Detecting potential seasonal over abstraction by irrigators.	By determining the distribution of cropping types and relating this to monitored water abstraction, possible cases of over abstraction may be determined.	X						X	
Changes in Basin Developments, Infrastructure and Assets such as: Farm storages, Bores, Levee's, plantations, floodplain harvesting infrastructure, plants, industries to assist with WSP development, and development proposals.	Knowledge of the distribution of water harvesting structures, industries and plants is required to assist with the development of water sharing plans and development proposals.	X	X	X	X				X
Clearly linking socio-economic changes to water reform through: the identification of predictor variables.	Potential indicators that may be measured using RS include: land use, length of sealed roads in towns, condition of sporting grounds, number of vacant houses, factories, silos, processing plant activity, changes in transport hubs within the	X	X	X	X			X	X

	basin.								
Information need	**Justification**	**Spatial scale of consideration**					**Temporal scale of consideration**		
		Site/reach	Asset	Floodplain	Valley	Basin	Event	Seasonal	Annual
Environmental Flows									
Antecedent catchment and floodplain conditions.	Improved information on catchment and floodplain wetness is required for better prediction flood timing and inundation extent and duration.			X	X	X	X	X	
Improved measurement of releases and abstractions from storages and river channels.	Accurate measurement of the amount of water released and abstracted from the river systems is needed more precise compliance and accounting purposes.	X	X	X	X		X	X	X

APPENDIX B.KEY TECHNOLOGIES AND DEVELOPMENTS

Optical Remote Sensing Platforms

Table 4.1 Operational satellite optical sensors and specifications.

Sensor and operating agency, launch, Design life (EOL)	Orbit & altitude (km) Inclination angle (°) Target revisit time	Swath width (km)	Imaging modes & wavelengths	Spatial resolution (m)	Radiom resol.	Data distributor and cost (if available)
Very High Resolution (< 5 m)						
IKONOS DigitalGlobe (USA) 1999-	680 km 60° 3 days	22	5 bands (PAN-VNIR): PAN (0.45-0.9 µm) Blue (0.45-0.52 µm) Green (0.51-0.6 µm) Red (0.63-0.7 µm) NIR (0.76-0.85 µm)	4 MS 1 PAN	8-11 bit	US Geological Survey (USGS) Archive: 4m: \$37/km^2 Tasking: \$290/km^2
Quickbird DigitalGlobe (USA) 2001-	450 km 97.2° 1-3.5 days	16.5	5 bands (PAN-VNIR): PAN (0.45-0.9 µm) Blue (0.45-0.52 µm) Green (0.52-0.6 µm) Red (0.63-0.69 µm) NIR (0.76-0.9 µm)	MS: 2.44 nadir 2.88 25° off-nadir PAN: 0.61 nadir 0.72 25° off-nadir	11 bit	Geoimage Archive: \$1,200 /25 km^2 2.4MS: \$43 /km^2 MS/PAN: \$51/km^2 Tasking: \$290 /km^2
Worldvew-1 DigitalGlobe 2007- EOL: 10-12 years	496 km 1.7 days	17.7	PAN (400-900 nm)	0.5	11 bit	Geoimage
Worldvew-2 DigitalGlobe 2009- EOL: 10-12 years	770 km 1.1 days	17.7	9 bands (PAN-VNIR): PAN (0.45-0.8 µm) Coastal (0.4-0.45 µm) Blue (0.45-0.51 µm) Green (0.51-0.58 µm) Yellow (0.585-0.625 µm) Red (0.63-0.69 µm) Red edge (0.705-0.745 µm) NIR1 (0.77-0.895 µm) NIR2 (0.86-1.04 µm)	0.46 PAN 1.85 MS	11 bit	Geoimage
GeoEye-1 DigitalGlobe(USA) 2008- EOL: 7 years	684 km 98° 3 days	15.2	5 bands (PAN-VNIR) Blue (0.45-0.51 µm) Green (0.51-0.58 µm) Red (0.655-0.69 µm) NIR (0.78-0.92 µm)	0.41 PAN 1.65 MS		Geoimage
Pleiades-1A, -1B(High-Resolution Imager, HiRI)	694 km 2 days	20	5 bands (PAN-VNIR): PAN (0.47-0.84 µm) Blue (0.44-0.54 µm) Green (0.5-0.6 µm)	0.5 – 2		ESA GMES Space Component (GSC) data

CNES, France 2011- (1A), 2012- (1B) EOL: 2016			Red (0.61-0.71 µm) NIR (0.77-0.91 µm)			access system
High resolution (5 – 10 m)						
SPOT-5 SPOT Image, France 2002- EOL: 5 years	822 km 98.7° 5-26 days	60	5 bands (PAN-VNIR-SWIR): B1 Green (0.5-0.59 µm) B2 Red (0.61-0.68 µm) B3 NIR (0.79-0.89 µm) B4 SWIR (1.58-1.75 µm) PAN (0.51-0.73 µm)	10 MS 5 PAN	8 bit	Astrium or Geoimage $6,300 full scene (60x60 km)
SPOT-6 SPOT Image 2012- EOL: 10 years	695 km 98.2° 1-5 days	60-120	5 bands (PAN-VNIR) B1 Blue (0.455-0.525 µm) B2 Green (0.53-0.59 µm) B3 Red (0.625-0.695 µm) B4 NIR (0.76-0.89 µm) PAN (0.45-0.75 µm)	8 MS 2 PAN	12 bit	Astrium or Geoimage
FORMOSAT-2 NSPO, Taiwan 2004-	891 km 97.7° Daily		PAN (0.45-0.9 µm) B1 Blue (0.45-0.52 µm) B2 Green (0.52-0.6 µm) B3 red (0.63-0.69 µm) B4 NIR (0.76-0.9 µm)	2 PAN 8 MS	8 bit	Astrium
RapidEye (Multi Spectral Imager, MSI) RapidEye AG, Germany 2008- EOL: 2015	622 km 97° 1 day	78	5 bands (VNIR): (0.44-0.51 µm) (0.52-0.59 µm) (0.63-0.685 µm) (0.69-0.73 µm) (0.76-0.85 µm)	6.5	12 bit	AAM Brisbane Archive: 1.28 USD/km^2 Tasking: 1.28 USD/km^2
ZY-3 China 2012-2016	506 km 97.42° 5 days	51	3 PAN cameras (500-800 nm) 4 bands MS: Blue (0.45-0.52 µm) Green (0.52-0.59 µm) Red (0.63-0.69 µm) NIR (0.77-0.89 µm)	2.1 nadir 3.6 fore/aft 5.8 MS	10 bit	
Moderate resolution (10 - 100 m)						
Landsat ETM+(Enhanced Thematic Mapper) LANDSAT-7 NASA, USA 1999-	705 km 98.2° 16 days	150	8 bands (VNIR-SWIR-TIR): PAN (0.52-0.9 µm) TM1Blue (0.45-0.52 µm) TM2Green (0.52-0.6 µm) TM3Red (0.663-0.69 µm) TM4NIR (0.76-0.9 µm) TM5MIR (1.55-1.75 µm) TM7MIR (2.08-2.35 µm) TIR (10.4-23.5 µm)	30 VIS 15 PAN 60 TIR	8 bit	Geoscience Australia (GA) Orthorect. 185x185 km Free
Landsat-8(Landsat Data Continuity Mission, LDCM) NASA, USA 2013- EOL: 5 yrs.	705 km 98.2° 16 days	185	Operational Land Imager (OLI) 9 bands (VNIR-SWIR, PAN): B1Coastal/Aerosol (0.43-0.45 µm) B2Blue (0.45-0.52 µm) B3Green (0.53-0.6 µm) B4Red (0.63-0.68 µm) B5NIR (0.85-0.89 µm) B6SWIR1 (1.56-1.66 µm) B7SWIR2 (2.1-2.3 µm)	15 PAN 30 MS 100 TIR	12 bit	USGS

			B8PAN (0.5-0.68 µm) B9Cirrus (1.36-1.39 µm) Thermal Infrared Sensor (TIRS) B10TIR1 (10.3-11.3 µm) B11TIR2 (11.5-12.5 µm)			
SPOT-4 SPOT Image, France 1998- EOL: 5 years	822 km 98.7° 26 days	60	5 bands (PAN-VNIR-SWIR): Green (0.5-0.59 µm) Red (0.61-0.68 µm) NIR (0.78-0.89 µm) SWIR (1.58-1.75 µm) PAN (0.61-0.68 µm)	20 MS 10 PAN	8 bit	Astrium or Geoimage $3,500 full scene (60x60 km)
ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) On-board Terra NASA, USA 1999- EOL:	705 km 98.2° 16 days	60	VNIR: 3 VIS (0.52-0.86 µm) 6 SWIR (1.6-2.43 µm) 5 TIR (8.125-11.65 µm)	15 30 SWIR 90 TIR		Geoimage or GA Single scene (60x60 km) AUD $145
Hyperion On-board EO-1 NASA, USA 2000- EOL: 5 years	690 km 98.2° 16 days	7.65	198 bands (VNIR-SWIR) (0.43 – 2.4 µm)	30	12 bit	USGS Free
IRS-P6Resourcesat-1 (Indian Remote Sensing Satellite) ISRO, India 2003- EOL: 5 years	817 km 98.7° 5 days	141 70 740	LISS-III (VNIR-SWIR): B2 (0.52-0.59 µm) B3 (0.62-0.68 µm) B4 (0.77-0.86 µm) B5 (1.55-1.75 µm) LISS-IV (VNIR) AWIFS (VNIR-SWIR)	23.5 LISS-III 5.8 LISS-IV 55 AWIFS	7 bit	National Remote Sensing Centre (NRSC)
IRS-P7 Resourcesat-2 ISRO, India 2011- EOL: 5 years	822 km 98.7° 26 days	141 70 740	LISS-III (VNIR-SWIR) LISS-IV (VNIR) AWIFS (VNIR-SWIR)	23.5 LISS-III 5.8 LISS-IV 55 AWIFS	10 bit	NRSC
DMC-2G (Disaster Monitoring Constellation – 2nd Generation) SSTL, UK 5-sat constell. 2005- (Beijing-1), 2008- (Deimos-1, UK-DMC2), 2011- (Nigeriasat-2, Nigeriasat-NX) EOL: 5 yrs.	686 km 98.2° Daily	650 20 20 300	3 bands (VNIR) Red (0.63-0.69 µm) Green (0.52-0.62 µm) NIR(0.76-0.9 µm) 4 bands (Nigeriasat-2, VNIR-PAN)	22-32 Nigeriasat-2: 2.5 PAN 5 MS 32 MS	8-10 bit	DMCii, UK
			Coarse resolution (> 100 m)			
MODIS (Moderate Resolution Imaging Spectroradiometer) On-board Terra	705 km 98.2° 1-2 days	2330	36 bands (VNIR-TIR) (0.4-14.5 µm)	250 B1-2 500 B3-7 1000 B8-36	12 bit	USGS or GA Free online

and Aqua NASA, USA 1999-2013 Terra 2002- Aqua						
AVHRR/3(Advanced Very High Resolution Radiometer) On-board NOAA-19 NOAA, USA 2009-2016	870 km 98.75°	3000	6 bands (VNIR-SWIR-TIR): VIS (0.58-0.68 µm) NIR (0.725-1.1 µm) SWIR (1.58-1.64 µm) SWIR (3.55-3.93 µm) TIR (10.3-11.3 µm) TIR (11.5-12.5 µm)	1100	10 bit	GA Free online

(*MS refers to multispectral, PAN: panchromatic).

Table 4.2 Operational airborne optical sensors and specifications.

Sensor and operating agency	Flying height (km)	Swath width (km)	Imaging modes & wavelengths	Spatial resolution (m)	Radiometric resolution	Data cost
			VHR and High resolution (< 10 m)			
HyMap HyVista Corp., Australia	1.5 – 4.5	2.3 – 4.6	128 bands VNIR-SWIR (0.45 – 2.5 µm) TIR (3-5 µm, 8-10 µm)	2 – 10	12 – 16 bit	\$100 - \$400 /km^2 (\$40,000 /day)
CASI-1500 (Compact Airborne Spectrographic Imager) ITRES, Canada	3.05	3.8 – 22.5	288 bands VNIR (0.38-1.05 µm)	0.25 – 1.5	14 bit	\$100 - \$400 /km^2
DMSI (Digital Multi-Spectral Imager) SpecTerra, W. Australia	0.4 – 3	5.1 – 15.4	4 bands Blue (0.44-0.46 µm) Green (0.54-0.56 µm) Red (0.64-0.76 µm) NIR (0.76-0.78 µm)	0.5 - 1.5	12 bit	\$50 - \$1,700 /km^2
Daedalus1268 ATM (Airborne Thematic Mapper) NERC, UK		*Alt./IFOV dep.	11 bands (0.42-2.35, 0.85-13 µm) 8 VNIR, 2 SWIR, 1 TIR	*Alt./IFOV dep.	16 bit	\$10 - \$16 /km^2 (\$2,700/hr.)
DAIS 7915(Digital airborne imaging spectrometer) DLR, Germany		*Alt./IFOV dep.	79 bands (VNIR-SWIR, 0.4 – 2.5 µm, 6 TIR (8-13 µm)	3 – 20	15 bit	

(*Determined by Instantaneous Field Of View, IFOV, and aircraft altitude).

Table 4.3 Operational airborne digital cameras and scanners and their specifications.

Sensor and operating agency	Flying height (km)	Swath width (km)	Imaging modes & wavelengths	Spatial resolution (m)	Radiometric resolution
			Very High Resolution (< 5 m)		
ADS40 (Airborne Digital Sensor) Leica Geosystems	2	2.4	PAN (0.47-0.68 µm) Red (0.61-0.66 µm) Green (0.54-0.59 µm)	0.1 – 0.5	8 bit

			Blue (0.43-0.49 µm) NIR (0.84-0.89 µm)		
ADS80 (Airborne Digital Sensor) Leica Geosystems	7.6	0.6-12	PAN (0.47-0.68 µm) Red (0.6-0.66 µm) Green (0.53-0.59 µm) Blue (0.42-0.49 µm) NIR (0.83-0.92 µm)	0.05 – 1	10-12 bit
DMC II$_{230}$ Z/I Imaging	2.5	0.6-1.5	PAN Red Green Blue NIR	0.1 – 1	14 bit
Ultracam Osprey Microsoft	5-7	1.2-11.7	PAN Red Green Blue NIR	0.1 – 1	14 bit
A3 Camera VisionMap	1.5-4.5	1-23	Red (0.6-0.74 µm) Green (0.51-0.58 µm) Blue (0.42-0.52 µm)	0.05 – 0.3	12 bit

(*Determined by Instantaneous Field Of View, IFOV, and aircraft altitude).

Table 4.4 Decommissioned optical sensors.

Sensor and operating agency, launch and EOL	Orbit & altitude (km) Inclination angle (°) Target revisit time	Swath width (km)	Imaging modes & wavelengths	Spatial resolution (m)	Radiometric resolution
			Moderate resolution (10 - 100 m)		
Landsat(Multispectral Scanner, MSS) LANDSAT 1-5 1972-1978 (L1) 1975-1983 (L2) 1978-1983 (L3) 1982-2001 (L4) 1984-2013 (L5) NASA, USA	920 km (L1-3) 99° 18 days 705 km (L4-5) 98° 16 days	185	5 bands (VNIR-SWIR-TIR): Green (0.5-0.6 µm) Red (0.6-0.7 µm) NIR (0.7-0.8 µm) NIR (0.8-1.1 µm) TIR (10.41-12.6 µm)	70 L1-3 237 TIR L1-3 82 L4-5	6 bit
LandsatTM(Thematic Mapper) LANDSAT-4/-5 NASA, USA 1982-2001 (L4) 1984-2013 (L5)	705 km 98.2° 16 days	150 185	7 bands (VNIR-SWIR-TIR): TM1Blue (0.45-0.52 µm) TM2Green (0.52-0.6 µm) TM3Red (0.663-0.69 µm) TM4NIR (0.76-0.9 µm) TM5MIR (1.55-1.75 µm) TM7MIR (2.08-2.35 µm) TIR (10.4-23.5 µm)	30 60 TIR	8 bit
SPOT-1/-2/-3 SPOT Image, France 1986-2003 (-1) 1990-2009 (-2) 1993-1996 (-3)	822 km 98.7° 26 days	60	4 bands (PAN-VNIR): Green (0.5-0.59 µm) Red (0.61-0.68 µm) NIR (0.78-0.89 µm) PAN (0.5-0.73 µm)	20 MS 10 PAN	8 bit
CHRIS (Compact High	681 km	14	19 programmable bands VNIR	18	12 bit

Resolution Imaging spectrometer) Proba ESA 2001-2012	97.9° 7 days		(0.42 – 1.05 µm) Or 63 bands Multi-angular pointing (+55°, +36°, 0°, -36°, -55°)	36	
CBERS-1 (China-Brazil Earth Resources Satellite) CRESDA (China), INPE (Brazil) 1999-2003 **CBERS-2** 2003-2009 **CBERS-2B** 2007-2010	778 km 98.5° 26 days	113 120 890	CCD camera (VNIR-PAN) IR-MSS (VNIR-SWIR-TIR) WFI (VNIR)	20 CCD 78 IR-MSS 156 TIR 258 WFI	8 bit
			Coarse resolution (> 100 m)		
MERIS (Medium Resolution Imaging Spectrometer) On-board ENVISAT ESA 2002-2012	800 km 3 days	1150	15 bands VNIR (0.39 – 1.04 µm)	300 land 1200 ocean	16 bit

Table 4.5 Future/proposed satellite optical sensors and specifications.

Sensor and operating agency, launch, Design life (EOL)	Orbit & altitude (km) Inclination angle (°) Target revisit time	Swath width (km)	Imaging modes & wavelengths	Spatial resolution (m)	Radiometric resolution
			Very High Resolution (< 5 m)		
GeoEye-2 DigitalGlobe(USA) 2013- EOL; 10 years	681 km 3 days	14.5	5 bands (PAN-VNIR) Blue (0.45-0.51 µm) Green (0.51-0.58 µm) Red (0.655-0.69 µm) NIR (0.78-0.92 µm)	0.34 PAN 1.36 MS	11 bit
Worldivew-3 DigitalGlobe 2014- EOL: 10-12 years	617 km < 1 day	13.1	17 bands (PAN-VNIR-SWIR): PAN (0.45-0.8 µm) Coastal (0.4-0.45 µm) Blue (0.45-0.51 µm) Green (0.51-0.58 µm) Yellow (0.585-0.625 µm) Red (0.63-0.69 µm) Red edge (0.705-0.745 µm) NIR1 (0.77-0.895 µm) NIR2 (0.86-1.04 µm) 8 SWIR (1.195-2.365 µm)	0.31-0.34 PAN 1.24-1.38 MS 3.7-4.1 SWIR	11 bit 14 bit SWIR
			High resolution (5 – 10 m)		
SPOT-7 SPOT Image 2014- EOL: 10 years	695 km 98.2° 1-5 days	60-120	5 bands (PAN-VNIR) B1 Blue (0.455-0.525 µm) B2 Green (0.53-0.59 µm) B3 Red (0.625-0.695 µm) B4 NIR (0.76-0.89 µm) PAN (0.45-0.75 µm)	8 MS 2 PAN	12 bit
			Moderate resolution (10 - 100 m)		
CBERS-3	778 km	120	IRS (PAN, VNIR-SWIR-TIR)	40	8 bit

CRESDA (China), INPE (Brazil) 2013-	98.5° 26 days	60 PAN 866 WFI-2	MS CCD camera (VIS) PAN (VNIR) WFI-2 (VNIR)	PAN/SWIR 80 TIR 20 MS CCD 5 PAN 10 MS 64 WFI-2	
Sentinel-2 ESA 2014- EOL: 7 years	800 km 98.62° 5 days (2 sats)	290	13 bands (VNIR-SWIR) B1-6 VIS (0.443-0.74 µm) B7-9 NIR (0.783-0.945 µm) B10-B12 SWIR (1.38-2.19 µm)	10 B2-4, 8 20 B5-8a, 11-12 60 B1,9,10	12 bit
Sentinel-3 ESA 2014- EOL: 7 years	814 km 98.65° 2 days (2 sats)	1270	21 bands (VNIR, 0.4-1.02 µm) Also dual-frequency SAR (Ku and C-band) and Radiometer	300	
EnMAP DLR, Germany 2016-	817 km 3 days	30	200 bands VNIR-SWIR (0.42 – 2.45 µm)	30	14 bit

Radar Remote Sensing Platforms

Table 4.6 Operational satellite SAR sensors and specifications.

Sensor and operating agency, launch, Design life (EOL)	Orbit & altitude (km) Inclination angle (°) Target revisit time	Swath width (km)	Imaging modes	Spatial resolution (m)	Incidence angle (°)	Data distributor and cost (if available)
			X-BAND (λ 2.5 – 3.75 cm)			
TSX-1(*TerraSAR-X)* DLR, Germany 2007-2013	Sun-synch 514 km 97.44° 11 days	10	High res Spotlight (HS): SP (HH or VV) or DP (HH/VV)	1.48-3.49	20-55	Astrium Archive-new: HS (10x5 km) or SL (10x10 km) EUR 3,375-6,750 SL (10x10 km) EUR 1,875-3,750 SC (100x150 km) EUR 1,375-2,750
		10	Spotlight (SL): SP (HH or VV) or DP (HH/VV)	1.48-3.49	20-55	
		15-30	Stripmap (SM): SP (HH or VV) or DP (HH/VV, HH/HV, VV/VH)	1.7-3.49	20-45	
		100	ScanSAR (SC): SP	1.7-3.49	20-45	
TDX-1 (*TanDEM-X)* DLR, 2010-2014 -EOL: 5 yrs.	Sun-synch 514 km 97.44° 11 days		Interferometric imaging: Bistatic mode Monostatic mode Along-track interferometry (ATI) Polarimetric interferometry	12 (DEM) (abs v.acc 10 m, rel v.acc 2 m)	25-55	DLR
			SAR imaging:			
		30	Stripmap DP	3		
		10	Spotlight DP	1		
		100	ScanSAR DP	16		
Cosmo-SkyMed	Sun-synch		Selectable single pol		25-50	ASI/e-geos

1-4*(Constellation of small Satellites for Mediterranean basin Observation)* ASI, Italy 2007 (-1/-2), 2008 (-3), 2009 (-4) EOL: 5 years	620 km 97.86° Daily-16 days	 10 30-40 100-200 30	(HH,VV,HV,VH) Spotlight Stripmap ScanSAR Ping pong or Stripmap – 2x selectable pol (HH, VV, HV, VH)	 1 3-15 30-100 15		
C-BAND (λ 3.75 – 7.5 cm)						
RADARSAT-1 CSA, Canada 1995-	Sun-synch 798 km 98.6° 24 days	45 100 150 300 500 75 170	Fine HH Standard HH Wide HH ScanSAR narrow ScanSAR wide Extended high Extended low	8 30 30 50 100 18-28 30	37-47 20-49 20-45 20-49 29-49 52-58 10-22	MDA CAD 3,600 Precision: CAD 4,500
RADARSAT-2 CSA, 2007-	Sun-synch 798 km 98.6° 24 days	20 50 50 100 150 300 500 75 25 25	Ultra-Fine SP Multi-look Fine SP Fine SP/DP Standard SP/DP Wide SP/DP ScanSAR Narrow SP/DP ScanSAR Wide SP/DP Extended High SP Fine QP Standard QP	3 8 8 25 30 50 100 18 12 25	30-49 30-50 30-50 20-49 20-45 20-46 20-49 49-60 20-41 20-41	MDA Spotlight: CAD 8,400 Fine: CAD 3,600-7,800 Std: CAD 3,600-3,800 Wide: CAD 3,600-3,800 ScanSAR: CAD 3,600-3,800 Extended: CAD3,600 QP: CAD 5,400-7,800

(*SP: single polarisation, DP: dual polarisation, QP: quad polarisation).

Table 4.7 Radiometers and scatterometers used for soil moisture estimation and their technical specifications.

Sensor and operating agency, launch, Design life (EOL)	**Orbit & altitude (km) Inclination angle (°) Target revisit time**	**Swath width (km)**	**Imaging modes**	**Spatial resolution (km)**	**Incidence angle (°)**	**Data distributor and cost**
TRMM NASA & NASDA 1997- EOL: 3 years	Sun-synch Circular 350 km 35°	758.5	TMI: 9 channel radiometer, dual pol,5 freq (10.65, 19.4, 21.3, 37.0, 85.5 GHz) Precipitation Radar (PR) VIS/IR Radiometer (VIRS)	50	52.8	Goddard DAAC Free online
SMOS	Sun-Synch	1000	L-band radiometer	35 - 50	0 - 50	ESA ERIN

ESA, 2009-	756 km 32.5° 3 days		(1.413 GHz) H and V pol			Free online
ASCAT On-board Metop-A EUMETSAT 2006-	837km 1.5 days	550	Scatterometer C-band (5.6 GHz) VV pol	25 - 50	25 - 65	EUMETSAT Data Centre Free online
GCOM-W, -C (Global Change Observation Mission) JAXA, 2012-	700 km 98.2° 2 days	1450	AMSR2: 14 channels, 6 freq (7 – 89 GHz) H and V pol			JAXA GCOM Data Providing Service Free online

Table 4.8 Operational airborne SAR sensors and specifications.

Sensor and operating agency	Flying height (km)	Swath width (km)	Imaging modes	Spatial resolution (m)	Incidence angle (°)
		X-BAND (λ 2.5 – 3.75 cm)			
STAR3i/IFSARE(Interferometric SAR – Elevation) Intermap, USA	12.2	10	X-HH	5 DEM (±1 m Vert. Acc. RMSE) 1.25 ORRI (±1.25 m Horiz. Acc. RMSE)	45
		L-BAND (λ 15 – 30 cm)			
PLIS(Polarimetric L-band Imaging SAR) Flinders Uni, Adelaide	0.3-3	0.1-2.2	L-band scatterometer Full pol Single pass InSAR	11-29	15-45
UAVSAR NASA JPL	13.8	16	L- full pol	2 rng	
		MULTI-FREQUENCY			
INGARA DSTO, Australia		12-48	X- and L- full pol Stripmap Spotlight Interferometric	2-8 0.3	45-89
GeoSAR Fugro EarthData, USA	10-13	10-12	X- and P- HH+HV or VV+HV	1.25-3 (X-) 1.25-5 (P-) 5 (DEM)	25-60

Table 4.9 Decommissioned SAR sensors.

Sensor and operating agency, launch and EOL	Orbit & altitude (km) Inclination angle (°) Target revisit time	Swath width (km)	Imaging modes	Spatial resolution (m)	Incidence angle (°)	Data distributor and cost
			C-BAND (λ 3.75 – 7.5 cm)			

ERS-1 (Earth Resources Satellite) ESA, 1991-2000	Sun-synch polar	100	C-VV	30x26.3	23	ESA/SARCOM EUR 180
ERS-2 ESA, 1995-2011	800 km 98.5° 35 days	100 5	SAR image mode C-VV SAR wave mode Wind scatterometer mode	26	20-26	ESA/SARCOM EUR 180
ENVISAT ASAR(Advanced SAR) ESA, 2002-2012	800 km 98.5° 35 days	100 100 400 400 5	Image mode (HH or VV) Alternating pol (VV+HH or VV+VH or HH+HV) Wide swath mode (HH or VV) Global monitoring mode (HH or VV) Wave mode (HH or VV)	30 30 150 1000 30	15-45	ESA/SARCOM EUR 300
L-BAND (λ 15 – 30 cm)						
JERS-1(Japanese Earth Resources Satellite) JAXA, 1992-1998	570 km 98.5° 44 days	75	L-HH	18	32-38	RESTEC L0: YEN 2,600 (~AUD 300) L2.1: YEN 2,500
ALOS PALSAR (Phase Array L-band SAR) JAXA, 2006-2011	691 km 98.16° 46 days	 70 70 30 350	L- Multiple modes Fine Beam Single HH Fine Beam Dual HH+HV Quad pol HH+HV+VH+VV Wide Beam HH	 10 20 30 100	 34.3-41.5 34.3-41.5 21.5 18-43	RESTEC YEN 52,500 (~AUD 659)
MULTI-FREQUENCY						
SIR-C/X-SAR (Shuttle Imaging Radar) NASA JPL, 1994	215 57° 2x11 day missions	15-90 15-40	C- and L- full pol (HH,HV,VH,VV) X-VV	10-200	49	USGS EROS Free online
SRTM (Shuttle Radar Topography Mission) NASA JPL, USA and DLR, Germany Feb 2000	233 km 57° 11 day mission	225	SIR-C HH+VV X-SAR HH+VV	30-90 (abs v.acc 16 m)	17-65	USGS EROS Free online

Table 4.10 Future/proposed satellite radar sensors and specifications.

Sensor and operating agency, launch, Design life (EOL)	Orbit & altitude (km) Inclination angle (°) Target revisit time	Swath width (km)	Imaging modes	Spatial resolution (m)	Incidence angle (°)
X-BAND (λ 2.5 – 3.75 cm)					
CSG-1, -2 (Cosmo-SkyMed Second Generation)	Sun-synch 620 km 97.8°	10 40 100, 200	Spotlight DP Stripmap DP ScanSAR DP	1 3 20, 40	

ASI, MiD	16 days	30	Ping-pong QP	15	
2015-2023 (CSG-					
1), 2016-2023					
(CSG-2)					
TerraSAR-X2	Sun-synch		Spotlight	0.5	
DLR, 2015-2018		10-40	Stripmap	1-4	
		50-500	ScanSAR	5-50	
C-BAND (λ 3.75 – 7.5 cm)					
Sentinel-1 A,B,C	693 km		VV+VH, HH+HV		20-45
ESA	98.18°	80	StripMap	5	
2013-2020 (A),	12 days	250	Interferometric Wide swath	5x20	
2015-2022 (B),		400	Extra wide swath	20x40	
2019-2026 (C)			Wave mode	5x5	
RCM (RADARSAT	592.7 km		HH,VV,HV,VH, compact pol		
Constellation	97.74°	500	Low resolution	100	19-54
Mission) C-1, C-2,	12 days	350	Med resolution (maritime)	50	19-58
C-3		30	Med resolution (land)	16	20-47
CSA		125	Med resolution (land)	30	21-47
2014-2021		30	High resolution	5	19-54
(C1,C2), 2015-		20	Very high resolution	3	18-54
2022 (C3)		350	Ice/oil low noise	100	19-58
		350	25 m ship mode	variable	19-58
S-BAND (λ 7.5 – 15 cm)					
NovaSAR-S	Sun-synch or		SP/DP/TP: (HH, HV, VH, VV)		
SSTL, UK	LI equatorial	15-20	Stripmap	6	16-34
2013-2020	580 km	100	ScanSAR	20	16-30
	Daily-4 days	150	ScanSAR wide	30	15-31
		750	Maritime surveillance	30	48-73
L-BAND (λ 15 – 30 cm)					
ALOS PALSAR-2	628 km	25	Spotlight SP	3x1	30-44
(Phase Array L-	97.9°	50	Ultra-Fine SP/DP	3	
band SAR)	14 days	50	High sensitive SP/DP/FP/CP	6	
JAXA, 2013-2017	66 days	70	Fine SP/DP/FP/CP	10	
	42 days	350	ScanSAR nominal SP/DP	100	
	14 days	490	ScanSAR wide SP/DP	60	
			(*SP: HH or VV or HV; DP: HH+HV or		
			VV+VH; FP: HH+HV+VH+VV; CP:		
			compact pol)		
SAOCOM (SAR	Sun-synch	20-40	Stripmap SP/DP	10	17-50.4
Observation and	620 km	100-150	TopSAR narrow SP/DP/QP	30-50	17.6-47.3
Communications	97.89°	220-350	TopSAR wide SP/DP/QP/CL	50-100	17.6-48.9
Satellite)	16 days (1 sat)		(*SP: HH or HV or VH or VV; DP:		
CONAE, Argentina	8 days (2 sats)		HH+HV or VV+VH; QP:		
and ASI, Italy			HH+HV+VH+VV; CL: RH+RV or		
4-Sat const.			LH+LV)		
2014-2019 (1A),					
2015-2020 (1B),					
2015-2020 (2A),					
2016-2021 (2B)					
EOL: 5 yrs.					
TanDEM-L	760 km	350	L-band SAR	20-100	26.3-46.6
DLR, 2017-2022			Single-pass InSAR		
	8 days		Polarimetry - quad pol		
			Wide swath mode		
P-BAND (λ 0.3 – 1 m)					
BIOMASS	642 km		P-band InSAR full pol	50x65	23-32

ESA		60	StripMap
2018-2021	25-45 days	105	ScanSAR

Table 4.11 Future/proposed satellite radars for soil moisture estimation and technical specifications.

Sensor and operating agency, launch, Design life (EOL)	Orbit & altitude (km) Inclination angle (°) Target revisit time	Swath width (km)	Imaging modes	Spatial resolution (km)	Incidence angle (°)
SMAP (Soil Moisture Active Passive) NASA JPL 2014-2017	Sun-synch 680 km 2-3 days	1000	L-band SAR VV,HH,HV L-band Radiometer	1-3 km 40 km	40
GPM (Global Precipitation Measurement) NASA (USA) and JAXA (Japan) 2014- EOL: 3-5 years	Non sun-synch 400 km 65° < 1 day	120-245 800	Dual freq Precipitation Radar (DPR): Ku (13.6 GHz) and Ka (35.5 GHz) GPM Microwave Imager (GMI) – 13 channels (10 – 183 GHz)	4 km	

Laser Scanning Systems

Table 4.12 Operational LiDARs and technical specifications.

Sensor and operating agency	Flying height (km)	Wavelength (nm)	Laser imaging specs	Laser capture	Elevation accuracy (cm)
ALTM Orion H300 **Orion M300** **Orion C300** Optech	0.15-4 0.1-2.5 0.05-1	1064 1064 1541	Pulse repetition rate: 50-300 KHz (H300, M300), 100-300 KHz (C300) Scan width (FOV): 0-50° Scan frequency: 0-90 Hz	Range: up to 4 range measurements (1st, 2nd, 3rd and last returns) Intensity: up to 4 returns for each pulse (12 bit)	<3-15, 1σ <3-10, 1σ <3-7, 1σ
ALTM Pegasus HA500 Optech	0.15-5	1064	Pulse repetition rate: 100-500 KHz Scan width (FOV): 0-75° Scan frequency: 0-140 Hz	Range: up to 4 range measurements (1st, 2nd, 3rd and last returns) Intensity: up to 4 returns for each pulse (12 bit)	<5-20, 1σ
LMS-Q780 Riegl	0.9-3.0		Pulse repetition rate: 400 KHz Scan width (FOV): 60°	Intensity: (16 bit) Av. Point density: 13/m^2	2, 1σ
LMS-Q680i Riegl	0.8-1.6		Pulse repetition rate: 80-400 KHz Scan width (FOV): 60° Scan speed: 10-200 lines/sec	Range: 1st pulse Intensity (16 bit) Av. Point density: 9/m^2	2, 1σ
VQ-480i	0.3-1.05		Pulse repetition rate: 50-	Intensity (16 bit)	2, 1σ

Riegl		550 KHz Scan width (FOV): 60° Scan speed: 10-150 lines/sec		
ALS70-CM **ALS70-HP** **ALS70-HA** Leica Geosystems	1.6 5 3.5	Pulse repetition rate: 120-200 KHz (CM, HA), 60-100 (HP) Scan width (FOV): 75°	Intensity: up to 3 returns (8 bit)	7-16, 1σ (CM, HA) 7-21, 1σ (HP)

APPENDIX C. POTENTIAL FOR REMOTE SENSING TO ADDRESS BUSINESS AND INFORMATION NEEDS OF THE MDBA

Abbreviations for sensors used in Tables 6.1 - 6.7 below.

Abbreviations	**Data source**
AP	Aerial photography
AV	Airborne Video
ALS	Airborne Laser Scanner
ALB	Airborne LiDAR Bathymetry
A-Ms	Airborne Multispectral
A-Hs	Airborne Hyperspectral
S-MsF	Spaceborne Fine resolution Multispectral
S-MsM	Spaceborne Moderate resolution Multispectral
S-MsC	Spaceborne Coarse resolution Multispectral
S-Hs	Spaceborne Hyperspectral
SAR	Synthetic Aperture Radar
InSAR	Interferometric SAR
S-Ra	Satellite Radar Altimetry
S-Pr	Spaceborne passive radar
Gr	Gravity instruments

CSIRO ranking applied to all metrics in Tables 6.1 - 6.7 to assess the usefulness of remote sensing to MDBA business and spatial information needs:

Operational	Well established image analysis routines and availability of sensors in Australia; map products produced routinely over broad areas; technical expertise and infrastructure available in Australia.
Feasible	Promising case studies but large-scale operational demonstrations are yet to be performed.
Likely	Present data are inadequate for generation of variables, but future availability of methods is anticipated.
Unlikely	Remote sensing is unlikely to measure the variable due to scaling issues or logistics.

Table 6.1 The usefulness of remote sensing for measuring key variables associated with physical form, as related to MDBA business and information needs (Source: adapted from CSIRO, 2003; Alluvium Consulting, 2011).

MDBA information need	**Broad SRA component (CSIRO, 2003)**	**Metric**	**Recommended and complementary data sources**	**Operational Australian examples**	**Opportunities**
Accurate prediction of flow/inundation relationships along the River Murray and floodplains	Floodplain	Floodplain size	ALS , S-MsM S-MsC, SAR, S-Pr	**Basin:** - GA provides catchment boundaries in Australia's River Basins (1997): Australia divided into 12 drainage divisions, 77 water regions and 245 river basins (Ranatunga *et al*. 2007).	
		Flood extent mapping		**Floodplain:** - Landsat archive used to identify flood events and develop flow/inundation relationship, inundation extent, duration and vegetation response (Shaikh *et al*., 1998, 2001; Tuteja *et al*. 2007). Lack of hydrologically significant images of the flood event (M. Shaikh, NOW). - MIKE 21 hydraulic modelling of Koondrook Perricoota forest wetlands validated by historic Landsat TM images (Tuteja and Shaikh, 2009). - Annual event: Floodplain flow extent/inundation can be shown quickly, albeit coarsely, using MODIS, which is useful for short-term environmental water planning (P. Driver, OEH/NOW). - ALS used for pool response modelling. Coarse if used in short-term but could be useful if quickly done (P. Driver). - Combination of optical and microwave sensors: MODIS, TRMM, Windsat and SMMR2 for daily monitoring of open water extent (B. Gouweleeuw, CSIRO). Daily satellite-derived information translates into mod-low accuracy. - Constrain inundation/hydrodynamic model with near real time satellite	**Site/reach:** - Site specific models under development (D. Jacobs, NOW). **Floodplain:** - Hydrodynamic models constrained by point gauge- and satellite-derived spatial information able to provide more accurate forecasts, optionally at sub-daily frequency (B. Gouweleeuw) - Possibility to blend daily low res info with high res, low frequency Landsat (B. Gouweleeuw) - Sentinel-1 will provide 30 m res radar data (B. Gouweleeuw). - Usefulness of wetland hydrodynamic models for short-term water decision making yet to be determined (P. Driver). - NOW continuing to use/develop simple wetland flow response models and also LiDAR wetland models (P. Driver). Methods are being employed by OEH for floodplains, but NOW could use this to keep developing WSP evaluation tools, and also use to assess 2-year, decadal and 100-year responses as well (P. Driver). - LiDAR has potential for flood inundation modelling, but needs tighter quality control (P. Carlile, MDBA). - Flood inundation needed and MDBA already

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
		🟩		derived open water extent/water height (B. Gouweleeuw). Applied to various floodplains (CSIRO/WfHC Flagship funded projects; Gouweleeuw *et al*. 2011; Karim *et al*. 2011). - MIKE21 hydrodynamic modelling using SRTM DEM and laser altimetry to reproduce floodplain topography. Calibrated using gauge water heights and MODIS and AMSR-E derived inundation extent maps. Flood extents and DEM combined to estimate inundation depth (Karim *et al*. 2011). Limited water gauge records in remote areas for calibration of flood models (Karim *et al*. 2011). - DPI VIC: mapping flood extent in riparian eco-sites. Using mixture modelling approach, DPI has done flood mapping in riparian sites of Barmah-Millewa, Gunbower, Koondrook-Perricoota forests over a number of years in the past. This activity is event-driven. Post-inundation periods are significant. Landsat has been frequently used for this purpose. For more recent flood mapping, SPOT images have been used. Flood extent information is considered important for hydrological modelling, among others (Abuzar and Ward, 2003). - Multi-date and multi-frequency ALOS PALSAR and TerraSAR-X data used to discriminate wetland surfaces and flooded/non-flooded vegetation. Change detection techniques applied to map wetland dynamics including successive phases of flooding and drying out of wetlands (Milne *et al*. 2008).	developing flood inundation model basin-wide (MDB-FIM; P. Carlile, MDBA). **Basin:** - Further development of integrated BOM forecasting service for flood, short-term flow, seasonal and long-term flow and water availability (Perkins *et al*. 2011). - VIC DSE: developing the Floodzoom tool for rural Victoria. It is based on the most recent DTMs (derived from existing LiDAR). Will be used to model predict flood risk and map flood depth and extent, and used to enhance flood emergency response.

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
				Basin: - Near real time satellite-derived open water extent and volume monitoring applied for Australian continent (CSIRO/WfHC Flagship funded projects; Ackland *et al*. 2012). - Statistical streamflow predictions using CSIRO's Bayesian joint probability model. Used operationally by BOM to produce seasonal streamflow forecasts at >20 sites in SE Murray Darling Basin (Perkins *et al*. 2011).	
		Proportions of major habitat types	S-MsM AP, A-Ms, A-Hs, S-MsF, S-Hs, SAR	**Floodplain:** - Spectral Angle Mapper (SAM) and ISODATA classification of surface water, marsh and floodplains subject to inundation (% cover of each class shown) using ALOS PALSAR in Macquarie Marshes (Milne *et al*. 2008).	**Floodplain:** - Wetland inventory and digital classification techniques (Fitoka and Keramitsoglou, 2008). Scale of imagery vs. habitat elements
	Pool assessment	Pool length	A-Ms AP, S-MsF, SAR		**Site/reach and Floodplain:** - Water body detection using optical indices or SAR, and GIS analysis (Tran *et al*. 2010). Water clarity, overhanging vegetation
		Pool width			
		Pool depth	A-Ms, ALB S-MsF, AP		**Site/reach and floodplain:** - Airborne sensors required for mapping depth in small water bodies (Leckie *et al*. 2005; Lejot *et al*. 2007; Lyon *et al*. 1992). - Stereogrammetry and LiDAR for measuring water depth (Feurer *et al*. 2008). Water clarity and very shallow water limits ALB
	Meso habitat diversity	Proportion of pool, riffle, run, backwater	A-Hs AP, AV, A-Ms, S-MsF, ALS, ALB		**Site/reach and Floodplain:** - Bare earth LiDAR DTM and ALB used in 2D hydraulic modelling and categorisation of mesohabitat (Hilldale *et al*. 2008). - Aerial video used to type meoshabitats where clearly visible (Alaska Energy Authority, 2012). River flow and sensor resolution dependent - Airborne multispectral data used to map morphologic units (eddy drop zones, glides, low

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
					and high gradient riffles, later scour pools, attached and detached bars, and large woody debris; Wright *et al*. 2000). - Hyperspectral data to map habitat types. SWIR proved most useful for discrimination (Legleiter, 2003; Marcus *et al*. 2003).
	Water body type assessment	Stream channel, floodplain etc.	S-MsF AP, AV, A-Ms, A-Hs, ALS, S-MsM	**Floodplain:** - ALOS PALSAR single- and multi-date composites used to identify ponded water, water-filled channels with overhanging vegetation and saturated soils in Macquarie Marshes (Milne *et al*. 2008).	**Floodplain:** - Optical data to map different types of flooded ponds: blue ponds with highly turbid water and no vegetation, and red ponds, with less turbid water and partial cover of aquatic plants (Gardelle *et al*. 2010). Flow volume dependent
	River bank	Bank slope	ALS S-MsF		**Site/reach and Floodplain:** - LiDAR DTM used to assess slope stability (Fallsvik, 2007). - Slope grids calculated using LiDAR DEMs (Gupta *et al*. 2011). Degraded accuracy of interpolated DEM. - Uncertainty of DEM in steep terrain
		Bank shape	ALS		**Site/reach and Floodplain:** - Use of LiDAR to extract channel cross sections and bank locations, identify geomorphic bank full water surface elevation, and measurement of channel width and bank and bluff heights (Passalacqua *et al*. 2012).
		Erosion type			- Combination of LiDAR and aerial photography or multispectral imagery to infer type
		Erosion extent	ALS	**Site/reach and floodplain:** - Riverbank erosion predicted from river properties defined by 250 m DEM for Australia (Hughes and Prosser, 2003).	- Subtract 2 bare earth DTMs to determine volume change over time. ALS could be used in erosion prediction (Thoma *et al*. 2005). - LiDAR used to quantify bank erosion. Volume change of river valleys measured using 2 LiDAR scans (Gupta *et al*. 2011).
		Slumping	ALS		
		Lateral scour	ALS, A-Ms		**Floodplain:** - Use of LiDAR derived DTM to map the depth of

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
					erosion where scour occurred (Kayen *et al*. 2006). - Use of LiDAR to map erosion, scour, liquefaction, lateral spread, slope failure and ground displacement following 2010 Chile earthquake and tsunami (Olsen *et al*. 2011).
	Hydrologic connectivity	Presence of levees	ALS AP, A-Ms, S-MsF, S-MsM	- Mapping of levees, channels, off-river storages and farm dams on Macquarie Marshes floodplains using LiDAR DEM, Landsat TM, SPOT and aerial photography (Steinfeld *et al.,* 2012).	- Derive from AP or LiDAR DEM. - Classification of high resolution MS data.
	Lateral and longitudinal inclusions to migration barriers	Distance to nearest weir	S-MsF AP, S-MsM		**Floodplain:** - Derived from analysis of DEMs or classification of MS satellite imagery. High quality DEM required.
		Number of barriers	S-MsF ALS, AP, S-MsM		
		Longitudinal connectivity - cumulative height of barriers upstream	ALS AP, S-MsF		
		Longitudinal connectivity - cumulative height of barriers downstream			
		Lateral connectivity - extent of floodplain alienation	S-MsF ALS, AP		
		Return period of bank full discharge	ALS, AP		
	Channel form assessment	Derivation from U-shape	ALS ALB		**Site and reach:** - River detection using LiDAR and analysis of profile shape (Lin *et al*. 2008). Benthic mapping determined by water clarity.
		Location of large woody debris	ALS AP, AV, A-Ms, S-Ms		**Site/reach and floodplain:** - Use of aerial video to map in-stream woody debris (Alaska Energy Authority, 2012). - Identification on LiDAR or aerial photography.
		Location of macrophytes	AP, A-Ms, A-Hs, S-MsF,ALS		- Classification of airborne or satellite imagery. - Identification on aerial photography or LiDAR.
		Amount of organic matter (particulate)	AP, A-Ms, A-Hs, S-Hs,S-MsF, S-MsM		- Classification of MS or HS data.

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
		Sediment type	A-Ms, A-Hs, S-MsF, S-MsM, S-Hs		- Classification of MS or HS data.
		Channel complexity	ALS		- LiDAR DEM analysis.
	Proportions of clay, silt, sand, gravel, cobble, boulders, bedrock and detritus	Proportion of bed material	A-Hs		- Classification of hyperspectral imagery. Water clarity and amount of overhanging vegetation
	Potential input of large woody debris	Snag recruitment per unit area of bank	S-MsF ALS, A-Ms, A-Hs, AP		- Classification of MS or HS imagery. R&D required on how to separate green vegetation from woody materials
	Sediment regime assessment	Stock density	S-MsM		- Use of thermal data to track heat signatures. R&D required
		Stock access to riparian areas	A-Ms AP, A-Hs, ALS		- Identify in high resolution imagery (e.g., erosion patterns, breaks in riparian zone, decrease in NDVI).
		Stock watering points			
		Channel movement, area of gullying	ALS AP, AV, S-MsF, S-MsM	**Site/reach and floodplain:** - Predictions of gully extent in Murray Darling Basin using aerial photographs (Hughes and Prosser, 2003).	**Site/reach and floodplain:** - Use of LiDAR to detect and map gullies and channels in a forested landscape (James *et al*. 2007). Systematic underestimation of gully depths and overestimation of gully top widths. - LiDAR used to discriminate and measure gully features, and corrections applied using field data to derive erosion volume estimates (Perroy *et al*. 2010). Field data required to verify and constrain DEM accuracy.
		Erosion (sheet or gullying)	ALS A-Ms, A-Hs, S-MsF, S-MsM		- High accuracy repeat LiDAR required to quantify sediment loss.
		% sediment patch	A-Ms AP, A-Hs, S-MsF, S-MsM		- Classification of MS or HS imagery or interpretation of aerial photography. Sediment must be spectrally distinct
		Sediment load	S-MsM AP, A-Ms, A-Hs, S-MsF		- Volume change from subtraction of 2 bare earth DTMs converted to mass wasting by multiplying with bulk density. Mass wasting rates

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
					converted to sediment load based on % of transportable material in bank strata (Thoma *et al*. 2005).
	River reach depth assessment	Depth	ALB A-Ms, AP		**Floodplain:** - LiDAR derived DTM and hydraulic modelling to simulate water depth and flow velocities (Mandlburger *et al*. 2009). - Airborne MS and colour photography used to map exposed gravel, shallow and deep water (Gilvear *et al*. 2004). Water clarity and sun glint lead to inaccuracies
		Current	ALB, InSAR		- SRTM and TerraSAR-X data for river current measurement (Romeiser *et al* 2005, 2011). - Use of coherent microwaves from ground, helicopter, aircraft and satellite InSAR (Plant *et al*. 2005). Lack of in situ monitoring stations. R&D required.
	Snag assessment	Snag number	A-Ms AP, S-MsF, ALS		- Identification LiDAR, aerial photography or fine resolution optical data. Water clarity& amount of algal growth may limit detection. Snags need to be exposed above water surface and be spectrally distinct. ALS data capture required during low flow and low turbidity conditions.
		Snag type			
		Snag diameter	ALS		
		Snag water column position	A-Ms, A-Hs		
		Snag distribution	A-Ms AP, S-MsF, ALS		
	Embeddedness	Embeddedness (amount of fine material around cobbles)	A-Hs		- Digital image classification Water clarity, biofilms, overhanging vegetation may interfere.

Table 6.2 The usefulness of remote sensing for measuring key variables associated with water quality, as related to MDBA business and information needs (Source: adapted from CSIRO, 2003; Alluvium Consulting, 2011).

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
Water quality in the rivers and floodplains of the Basin	Water processes – primary indicators assessment	Pelagic Chlorophyll-a (Chl-a)	A-Hs S-Hs,S-MsF, S-MsM	**Floodplain:** - Turbidity, Total suspended solids, total Phosphorous, total Nitrogen, DO, pH, salinity and temperature. To be reported as component of NSW River Condition Index. Provided to SoE reporting, NSW MER reporting, NSW State Plan reporting, Basin Plan reporting. Used for internal business, e.g., planning and licensing. Available to external NSW NRM agencies and research groups. Publically available data (L. Bowling/M. Muschal, NOW). High water turbidity* Weather conditions* Bias in temporal observations due to cloud, haze, fog, smoke or dust* Shading by overhanging vegetation* Lack of bio-optical information for parameterisation and validation of water quality information* (*Common to all water quality parameters derived from remote sensing; Dekker and Hestir, 2012). High water turbidity can hamper the detection of chlorophyll and other phytoplankton pigments.	**Basin:** - Regression relationships developed using CASI data. Chl-a identified with r^2 of 0.75 from ratio of 2 red edge bands (705/675 nm; Shafique *et al*. 2003).
	Water processes –	Coloured dissolved organic matter	S-MsC, S-MsM, S-MsF, S-Hs	**Floodplain:** - Use of coarse (1000 m MODIS, MERIS,	- Potential use of coarse resolution (500 MODIS) to estimate CDOM (Dekker and Hestir, 2012).

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
	ancillary indicators assessment	(CDOM)		OCM-2, VIIRS and JPSS), moderate (Landsat) and fine (IKONOS, Quickbird, SPOT-5, GeoEye, RapidEye, Worlview-2) resolution optical sensor data to estimate CDOM (Dekker and Hestir, 2012). - Use of Hyperion data and physics-based inversion method to map CDOM in Moreton Bay waters (Brando and Dekker, 2003).	- Future use of moderate (Sentinel-2) and coarse resolution optical (Sentinel-3) and hyperspectral sensor data (Dekker and Hestir, 2012).
		Turbidity	S-MsC, S-MsF, A-Hs, S-Hs	**Floodplain:** - Use of optical data at coarse (1000 m MODIS, MERIS, OCM-2, VIIRS and JPSS), moderate (Landsat) and fine (IKONOS, Quickbird, SPOT-5, GeoEye, RapidEye, Worlview-2) spatial resolution (Dekker and Hestir, 2012). - Use of CASI to map turbidity on Hawkesbury River and Lake Mokoan (Jupp *et al*. 1994a, b).	- Potential to use coarse spatial resolution optical data (250-500 m MODIS; Dekker and Hestir, 2012). - Future use of moderate (Sentinel-2) and coarse resolution optical (Sentinel-3) and hyperspectral sensor data (Dekker and Hestir, 2012).
		Secchi Disk (SD) transparency	S-MsC, S-MsF, S-Hs	**Floodplain:** - Use of optical data at coarse (1000 m MODIS, MERIS, OCM-2, VIIRS and JPSS), moderate (Landsat) and fine (IKONOS, Quickbird, SPOT-5, GeoEye, RapidEye, Worlview-2) spatial resolution (Dekker and Hestir, 2012).	- Potential to use coarse spatial resolution optical data (250-500 m MODIS; Dekker and Hestir, 2012). - Future use of moderate (Sentinel-2) and coarse resolution optical (Sentinel-3) and hyperspectral sensor data (Dekker and Hestir, 2012). - Use of empirical algorithm to relate in situ measurements to Landsat reflectance for operational monitoring of SD transparency (Olmanson *et al*. 2011). Extensive, long-term in situ measurements required for regression analysis.
		Temperature	S-MsM	**Floodplain:** - TIR data used to estimate temperature of water surface skin layer (Dekker and Hestir, 2012). - 60 m ASTER thermal data provides highest resolution to measure temperature (Turral *et al*. 2008).	- 2 thermal bands are required to compensate atmospheric effects (Tran *et al*. 2010).
	FARWH water quality	Dissolved oxygen (DO)		R&D required.	- Camera (Kodak 2443 false CIR) and Wratten 16 orange gelatine filter mounted on aircraft. The

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
	metrics				sensor renders healthy water saturated with DO as brilliant blue and septic water (near 0 DO) black (EPA, 1973).
		Total nitrogen (N)		**Floodplain:** - Potentially derived via a proxy: in a N-limited system, there may be a proxy relationship between Chlorophyll and total N (Dekker and Hestir, 2012).	
		Total phosphorous (P)		**Floodplain:** - Potentially derived via a proxy: in a P-limited system, there may be a proxy relationship between Chlorophyll and total P (Dekker and Hestir, 2012).	
		pH		**Floodplain:** - Mapped by association of vegetation classes (Turral *et al*. 2008). - IKONOS imagery and ground statistics used to infer the distribution of pH using a Bayesian post classifier (Turral *et al*. 2008). No direct method of estimation.	
		Total suspended matter (TSM)	S-MsC, S-MsF, A-Hs	**Floodplain:** - Use of optical data at coarse (1000 m MODIS, MERIS, OCM-2), moderate (Landsat) and fine (IKONOS, Quickbird, SPOT-5, GeoEye, RapidEye, Worlview-2) spatial resolution (Dekker and Hestir, 2012). - Use of CASI to map TSS on Hawkesbury River and Lake Mokoan (Jupp *et al*. 1994a, b). - Use of Hyperion data and physics-based inversion method to map TSM in Moreton Bay waters (Brando and Dekker, 2003).	- Potential to use coarse resolution optical sensor data (250-500 m MODIS, VIIRS and JPSS; Dekker and Hestir, 2012). - Future use of moderate resolution (Sentinel-2), coarse resolution (Sentinel-3) optical and hyperspectral sensor data (Dekker and Hestir, 2012).
		Chlorophyll (CHL)	S-MsC, S-MsF, A-Hs, S-Hs	**Floodplain:** - Use of optical data at coarse (1000 m MODIS, MERIS, OCM-2, VIIRS, JPSS) and fine (Worldview-2) spatial resolution (Dekker and Hestir, 2012). Moderate-coarse resolution optical sensors (MODIS, MERIS and Landsat) are limited in detection of small water bodies and narrow	- Potential to use Landsat and high resolution optical sensor data (Dekker and Hestir, 2012). - Future use of the Ocean Land Colour Instrument on board Sentinel-3 and future hyperspectral sensors (Dekker and Hestir, 2012). - Use of empirical algorithm to relate in situ measurements to Landsat reflectance for operational monitoring of CHL (Olmanson *et al*.

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
				river channels. - Hampered by high water turbidity. - Use of CASI to map CHL on Hawkesbury River and Lake Mokoan (Jupp *et al*. 1994a, b). - Use of Hyperion data and physics-based inversion method to map CHL in Moreton Bay waters (Brando and Dekker, 2003).	2011).
		Cyanobacterial pigments	S-MsC, S-MsF, A-Hs	**Floodplain:** - Use of optical data at coarse (MERIS, OCM-2) and fine (Worldview-2) spatial resolution (Dekker and Hestir, 2012). - Use of CASI to map cyanobacterial pigments on Hawkesbury River and Lake Mokoan (Jupp *et al*. 1994a, b).	- Potential to use coarse (1000 m MODIS, VIIRS and JPSS) and moderate (Landsat) and high spatial resolution optical sensor data (Dekker and Hestir, 2012). - Future use of hyperspectral satellite and low resolution ocean-coastal satellite data (Dekker and Hestir, 2012).
		Vertical attenuation of light coefficient (K_d)	S-MsC, S-MsM, S-MsF, S-Hs	**Floodplain:** - Use of optical data at coarse (1000 m MODIS, MERIS, OCM-2, VIIRS and JPSS), moderate (Landsat) and fine (IKONOS, Quickbird, SPOT-5, GeoEye, RapidEye, Worlview-2) spatial resolution (Dekker and Hestir, 2012). - Use of Hyperion data and physics-based inversion method to map K_d in Moreton Bay waters (Brando and Dekker, 2003).	- Potential to use coarse resolution (250-500 m MODIS) optical data (Dekker and Hestir, 2012). - Future use of coarse resolution ocean-coastal, moderate resolution MS and hyperspectral satellite data (Dekker and Hestir, 2012).
Mapping of algae/blackwater events	Cover of algae/periphyton/biofilm	Proportion of surface covered by algal categories	A-Hs A-MsF, AP	**Floodplain:** - Optical green wavelengths considered most suitable for detecting submerged macrophytes, followed by red and red edge regions (Turral *et al*. 2008). Mapping macrophytes requires separation of green signal from water signal: requires optical model and good radiometric correction of data.	- Spectral unmixing of hyperspectral imagery.
		Proportion of surface covered by fine silt	A-Hs		R&D required
		Type of biofilm			
		Thickness of biofilm			
	Blackwater event	Organic matter content	S-MsM	**Floodplain:** - Blackwater real time monitoring network in Murray Valley, 9 stations currently extending to ~15 stations in 2013 (L. Bowling/M. Muschal, NOW). - Landsat before and after event images used	- Following parameterisation of inversion algorithms for the high organic matter associated with black water events, it will be possible to inform on water quality (Dekker and Hestir, 2012).

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
				to identify blackwater events (Dekker and Hestir, 2012). Detection of rapid change during extreme events is more difficult.	
Catchment salinity monitoring		Salinity (electrical conductivity)	S-Hs, S-MsM, S-Pr	**Floodplain:** - Use of electromagnetic sensors mounted on low-altitude helicopter, to map salinity in Murray floodplain (Turral *et al*. 2008). - Airborne electromagnetic used by BRS to map catchment salinity for National Land & Water Audit (NLWA).	- Successful attempts in agricultural catchments using SAR, hyperspectral and VNIR imagery and extensive GIS (topography, geology, geomorphology, soils, depth to water table, and groundwater quality; Turral *et al*. 2008). - Use of PALS sensor to estimate ocean surface salinity (Wilson *et al*. 2001).

Table 6.3 The usefulness of remote sensing for measuring key variables associated with aquatic biota, as related to MDBA business and information needs (Source: adapted from CSIRO, 2003; Alluvium Consulting, 2011).

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
Past and present ecological condition and response of fish/birds/vegetation at key environmental assets and between icon sites	Emergent aquatic macrophyte diversity, area and relative abundance	List of species	A-Hs, S-Hs, A-Ms		R&D required. Overhanging canopy might obscure vegetation. Species must be spectrally distinct.
		Relative abundance of each species			
		% native macrophyte species			
		Cover of aquatic macrophytes	A-Ms, A-Hs, S-MsF, S-MsM, SAR		- Aerial video to capture mesohabitat (Alaska Energy Authority, 2012) Overhanging canopy and water clarity may limit detection. - Classification of MS or HS imagery
		% macrophyte cover within patches	A-Ms, A-Hs, S-MsF		
		% macrophyte area	AP, A-Ms, A-Hs, S-MsF, S-MsM		
		Stem density of aquatic macrophytes	A-Ms, S-MsF, ALS		- Infer through relationship with Leaf Area Index, derived from MS or LiDAR data
	FARWH metrics	Richness (fish)			- Potentially assess through habitat models, calibrated by vegetation composition (Turral *et al*. 2008).

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
		Proportion alien (fish)			
		% native species (fish)			
		Richness (birds)	AP	**Floodplain:** - Aerial counting (R. Kingsford, UNSW).	- Map bird habitat as surrogate richness measure.
		Cover of aquatic weeds	A-Ms, A-Hs, S-MsF, S-MsM		**Site/Reach:** - Quickbird imagery used to map emergent wetland communities and invasive Phragmites australis and Typha species (Ghioca-Robrecht *et al*. 2008).
	Riparian vegetation width	Distance from edge of channel to cleared/developed land	A-Ms AP, AV, S-MsF, S-MsM, S-Hs	**Floodplain:** - LiDAR and Quickbird derived metrics used to map width of riparian zone. Strong correlation with field measurements (r=0.82; Arroyo *et al*. 2010).	
		Channel width	ALS	**Floodplain:** - LiDAR and Quickbird derived metrics used to map width of streambed. Strong correlation with field measurements (r=0.98; Arroyo *et al*. 2010).	
		Width of floodplain	AP, AV, ALS, A-Ms, S-MsF, S-MsM		
		Density of floodplain vegetation	AV,A-Ms, S-MsF, S-MsM, S-Hs		
	Riparian vegetation cover	% cover shrubs <5 m	A-Ms AP, AV, A-Ms, S-MsF, S-Hs		- Use of LiDAR, field data and random forest algorithm to map understorey shrubs (Martinuzzi *et al*. 2009). Vegetation must be spectrally and structurally distinct and visible from sensor above.
		% cover understorey	ALS	- LiDAR derived understorey classification (Turner, 2007). Depends on density of tree cover above.	- Understorey LiDAR cover density created by filtering understorey points using intensity values (Wing *et al*. 2012).
		% cover herbs			
		% cover of floodplain	AP, AV, A-Ms, S-MsF, S-Hs		
	Riparian habitat fragmentation	Length of bank with vegetation >5 m wide	S-MsF AP, AV, ALS, A-Ms	**Floodplain:** - Derived from LiDAR as input to Index of Stream Condition (ISC) for state-wide	May require vegetation to be spectrally and structurally distinct
		Vegetated stream length	AP, AV, A-Ms, S-MsM,		

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
			S-Hs	assessment of stream condition (VIC DSE, 2012). - Classification of Landsat TM for Lockyer Catchment, QLD, to quantify structural change in riparian habitat (Apan *et al.*, 2002).	
		Number of gaps	AP, AV, A-Ms, S-MsF, S-Hs		
		Average patch size			
		Patch size	AP, AV, A-Ms, S-MsM, S-Hs		
		Length of gaps			
		Riparian connectivity			
	Riparian canopy complexity	% cover of trees >5 m	A-Hs AP, AV, A-Ms, ALS, S-MsF, S-Hs		
		% cover of shrubs	AP, AV, A-Ms, ALS, S-MsF, S-Hs		Shrubs must be spectrally and structurally distinct and not overshadowed by trees
		% cover of understorey	ALS, S-MsM, S-Hs		- Use of LiDAR, multispectral or hyperspectral data (spectral unmixing, fractional cover estimates).
		% cover of ground vegetation			
	Standing litter component	Depth and % cover of litter in quadrats	A-Hs, S-Hs, ALS		- Spectral unmixing of HS data to retrieve fractional cover - LiDAR to estimate litter depth Litter might be obscured by canopy
	Riparian demography	Proportion of individuals of each species of major riparian plants in each age class	A-Ms ALS, A-Hs, SAR		Age discrimination requires more R&D. Vegetation must be spectrally and structurally distinct.
	Riparian vegetation density	Basal area of dominant species	ALS SAR, S-MsF		- LiDAR height and intensity data. Allometrics not well defined for many species, particularly multi-stems.
		Stem density of dominant species	ALS SAR		
	Vegetation overhang	Distance of canopy from channel	A-Ms AP, ALS, S-MsF	**Floodplain:** - LiDAR and Quickbird derived metrics used to determine the distribution of overhanging vegetation within the streambed (Arroyo *et al*. 2010). - Derived from LiDAR as input to Index of Stream Condition (ISC) for state-wide assessment of stream condition (VIC DSE, 2012).	Access to accurately geocoded high resolution data.
	Riparian regeneration	Expected future proportion of individuals	S-MsF A-Ms, A-Hs, S-MsF,		- Classification and change detection.

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
		of large and common species in each age class	SAR		
	Riparian vegetation species	Dominant tree and shrub species	A-Hs ALS, S-MsF	**Floodplain:** - Derived from LiDAR as input to Index of Stream Condition (ISC) for state-wide assessment of stream condition (VIC DSE, 2012).	Vegetation types must be spectrally and structurally distinct.
		Vegetation association	A-Hs AP, A-Ms, ALS, S-MsF, S-MsM, S-Hs	**Floodplain:** - LiDAR and Quickbird derived metrics used to map riparian vegetation, streambed, bare ground, woodlands and rangelands (Arroyo *et al*. 2010). - Landsat based methods for mapping riparian forest in QLD Murray Darling Basin and Bulloo catchments (Clark and Healy, 2012). Need for high resolution data (SPOT-5) recognised. - Riparian vegetation extent for NSW mapped using existing Landsat woody vegetation extent layer and a new stream order layer. Veg extent within 30 m buffer around rivers with streams orders >3 is mapped. SPOT-5 and ADS40 used in validation (Garlapati *et al*. 2010).	
		% native species	A-Hs S-MsF		- Digital image classification, spectral unmixing, integration with other RS data Feasible when only few species are present that are spectrally/structurally distinct.
		Riparian evenness	A-Hs		
		Vegetation condition	S-MsF, S-MsM, S-MsC A-Ms, A-Hs, S-Hs, ALS, SAR	No agreed definition of condition or standard approaches to measurement. **Site/reach:** - SRA model and TLM monitoring. Could be supplemented by Worldview-2 (2 m res, 8 bands) data for classifying vegetation type and condition (P. Carlile, MDBA).	**Site/reach:** - Collection of training data in dry times to support classification of vegetation types (P. Carlile). **Floodplain:** - Inclusion of seasonal imagery to improve predictive power of SCT, and ongoing ground survey for validation of model beyond reference

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
				Site/reach and floodplain: - Detailed vegetation condition assessment using NDVI, Landsat and SPOT (P. Driver, OEH/NOW). - Assess trends in greenness indices to see changes in vegetation amounts associated with increasing CO_2 levels (will impact water yields from high water yielding catchments). Trends can be linked to biophysical model to understand the likely magnitude of change (McVicar *et al*. 2010; Donohue *et al*. 2011). - Modelling approach (neural networks) to estimate stand condition in (i) Victorian Murray River floodplain and (ii) Living Murray Icon Sites, using Landsat-5 and ground data (Cunningham *et al*. 2009b, 2011). - Development of Stand Condition Tool (SCT) to predict stand condition of Icon sites. Plot based measurement of % live basal area, plant area index and crown extent at reference sites. Model predictions suggested that water availability was insufficient to maintain majority of forests/woodlands in good condition, and the latter remain restricted to limited areas with permanent water (Cunningham *et al*, 2011). Prediction accuracy dependent on modelling approach and data selection (optical image quality). Calibration of models requires reference sites representative of all stages of condition. Need to establish reference (baseline) condition. Need to quantify uncertainty.	sites (Cunningham *et al*. 2011). - May use surrogates for vegetation condition such as soils and NDVI, or LiDAR for health assessment (P. Carlile). - Set of RS derived indices to assess the integrity of natural habitat: 6 habitat extent indices (natural cover, river-stream corridor integrity, pond/lake buffer integrity, wetland extent, standing water body extent), 4 habitat disturbance indices (dammed stream flowage, channelized stream flowage, wetland disturbance, and habitat fragmentation by roads) and 1 composite index (Tiner, 2004). **Basin:** - Accessing the Landsat archive, combined with MODIS to improve temporal resolution (P. Carlile). - MODIS includes coarse measure of vegetation health (NDVI), a form of condition assessment (P. Driver). - Long time-series reflective data (e.g., Landsat, SPOT) to determine maximum flush and duration of flush for a variety of inundation event sizes. Using such an approach for events of similar magnitudes allows vegetation resilience to be monitored (T. McVicar, CSIRO). - AVHRR thermal imagery used to generate Normalised Temperature Difference Index (NTDI), a proxy for soil moisture and evapotranspiration ratio. Use NTDI with NDVI to understand soil moisture and vegetation response. Ratio of NDVI to NDTI can yield useful metrics on vegetation health and trends such as desiccation in wetlands (Turral *et al*. 2008).

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
				Basin: - VIC DSE Ecological Vegetation Class (EVC) mapping of native vegetation quality based on Habitat Hectares approach. Integration of site condition and landscape model. EVC benchmarks have been established so veg condition at site scale can be assessed against reference condition (VIC DSE, 2007). - MODIS time-series to generate vegetation greenness index (250 m res, 16 day intervals, since 2000), vegetation wetness index (250 m res, 16 day intervals, since 2000) and vegetation stress based on land surface temperature (1000 m, 8 day interval, since 2000; H. Hemakumara/M. Mitchell, NOW). - VIC DPI Land Use Information System and data derived from ET projects could contribute to this goal, including work already undertaken exploring linkages between riparian vegetation, NDVI, ET and river flow records (Sheffield *et al*. 2012).	
		Foliar chemistry (Jones *et al.,* 2013)	A-Hs, S-Hs S-MsF	**Site/reach:** - Optically derived vegetation indices to estimate Chlorophyll content using reflectance in far red (Datt, 1998) - Partial least squares (PLS) and multiple regression models (MLR) to estimate crown nitrogen (N) content using high spatial resolution hyperspectral imagery (Coops *et al*. 2003). Scaling up from leaf to canopy scale can be difficult.	**Site/reach:** - Optically derived vegetation indices to estimate Nitrogen content: NDRE (Barnes *et al*. 2000) and NDNI (Fourty *et al* 1996). - Optically derived vegetation indices to estimate Chlorophyll content using reflectance in far red (Curran *et al*. 1990; Gitelson and Merzlyak, 1994; Vogelmann *et al*. 1993) and NIR and blue/green wavelength regions (Daughtry *et al*. 2000; Haboudane *et al*. 2002; Sims and Gamon, 2002). - Optically derived vegetation indices to estimate carotenoids using VIS reflectance (Gamon *et al*. 1992; Gitelson *et al*. 2002). - Optically derived vegetation indices to estimate lignin content (Serrano *et al*. 2002).

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
					- Use of spectral ratios to normalize differences in illumination intensity arising from overhanging canopy (Osborne *et al*. 2004). - Use of MS canopy reflectance and radiative transfer models to estimate leaf chlorophyll content (Jacquemoud *et al*. 1995). **Floodplain:** - Future hyperspectral satellites (EnMAP) will offer advanced capabilities for estimating foliar chemistry.
	River Condition	River Condition Index (RCI)		**Basin:** - NOW has developed RCI for long-term reporting on river health. Multiple indices are combined into a single condition score that can be applied at a range of spatial scales. Measures of in stream value and risks to in stream value (i.e., resilience) are also produced (Healey *et al*. 2012). RCI is developed using existing datasets and the approach is limited by the lack of available state-wide targeted data at the required scale to enable a high degree of confidence. RCI products have not been validated.	
		Index of Stream Condition (ISC)		**Basin:** - VIC DSE developed ISC for state-wide assessment of stream condition. ISC is a composite index of condition, comprising hydrology, water quality, aquatic life, streamside zone and physical form components. Metrics are derived from LiDAR, aerial photography and field survey (VIC DSE, 2012).	
Predicting, planning and evaluating the ecological response to environmental watering		Murray Flow Assessment Tool (MFAT)	S-MsM S-MsC	**Floodplain:** - MODIS and Landsat: Compare predicted non-flood NDVI of floodplain (or parts thereof) to observed NDVI to determine vegetation response to supply of flood	**Floodplain:** - The MFAT, while a useful approach as it allows habitat suitability scoring, has been shown to predict vegetation types based on a flow regime where they do not exist (i.e., poorly calibrated

MDBA information need	Broad SRA component (CSIRO, 2003)	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
				water (N. Sims, CSIRO). - Combining RS classification as input into MFAT like assessment or Conservation Planning Framework (P. Carlile, MDBA).	preference curves). Present vegetation mapping may be a poor representation of the actual location of vegetation (P. Carlile). - Preliminary demonstration of time-series NDVI method in Sims & Colloff (2012). Further development to increase applicability to other floodplains would be relatively straightforward (N. Sims).
		Plant water requirements	AP, S-MsM	**Floodplain:** - Hydrology-driven approach to determining environmental water requirements of Gwydir wetlands. Quantity of water required to achieve inundation of areas of water couch and rushes was determined by calculation of a water budget, and establishing a relationship between stream flow and area inundated using remote sensing and streamflow records (Bennett and McCosker, 1994).	- Hydrology and ecology-driven approaches to determining environmental water allocations to wetlands. Use of RS to derive inputs for models (Davis *et al*.2001).

Table 6.4 The usefulness of remote sensing for measuring key variables associated with hydrological disturbance, as related to MDBA business and information needs (Source: adapted from CSIRO, 2003; Alluvium Consulting, 2011).

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
Estimation of floodplain harvesting and losses from ET	Loss from Evapotranspiration (ET)	A-Ms, S-MsM, S-MsC	**Floodplain:** - Thermal resistance energy balance model methods (using Landsat, MODIS or AVHRR) to estimate actual evapotranspiration (ETa, Glenn *et al*. 2011; Kalma *et al*. 2008; Van Niel *et al*. 2012; Guerschman *et al*. 2009b). MODIS based hybrid method using VIS-SWIR data for scaling ETp to ETa. Open Water Likelihood (OWL) mapping (T. McVicar, CSIRO). - Use both thermal and hybrid approach to check each other. MODIS approach is used operationally in	**Floodplain:** - Improve model estimates of ETa by expanding flux tower networks and improving ground methods (Glenn *et al*. 2011). - Resource hungry: to achieve high accuracy for mapping for compliance purposes, the results need to be validated (visual interpretation and field visits) which requires resources (M. Shaikh).

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
			BoM WD. Thermal approach is near operational in CLW (T. McVicar). - Using ETa estimates time-series of floodplain ETa can be gained from overlaying vectors and cookie cutting from the raster data (T. McVicar). Cloud cover in imagery. Daily to monthly frequency, depending on needs. - Floodplain harvesting assessed using dynamics of OWL that can be calculated using Landsat-MODIS blended imagery that has Landsat resolution and MODIS frequency for key sites (Guerschman *et al*. 2011; Emelyanova *et al*. 2012a, 2012b). - Use of TIR, SWIR and/or vegetation indices, combined with meteorological data to estimate ETa (Glenn *et al*. 2011). Ground and RS estimates are assimilated into Australian Water Resources Assessment, which produces annual estimates of continental water balance. Best ETa models have error of 10-20 % in Australia. - Catchment water balance can be determined from direct estimation of ET using SEBAL and thermal data (e.g., AVHRR and MODIS; Tural *et al*. 2008). - VIC DPI: METRIC implementation of SEBAL algorithm to generate pixel scale estimates of ET using inputs derived from Landsat and meteorological data. Irrigated crop ET quantified for main crops/pastures in Murray Darling Basin major irrigation regions (Whitfield *et al*. 2010, 2011, 2012).	
	Water balance modelling	S-MsC, S-MsM	**Basin:** - Australian Water Resources Assessment system Landscape model (AWRA-L): 1D grid based biophysical model that aims to inform on historic, present and future water balance, in an operational manner. Model typically applied at 1-10 km resolution. Some model inputs derived from satellite imagery, e.g., MODIS used to estimate albedo, emissivity, LAI and vegetation indices (NDVI, EVI). Validation using point gauge data and satellite observations (van Dijk, 2010). A linked sub model has	- Sub model AWRA-G (deeper groundwater dynamics) is in development phase (Band, 2011). - Use MODIS or Landsat data to generate continuous land cover, rather than using limited number of classes (Band, 2011). - Incorporation of RS derived products on canopy dynamics and soil moisture (Band, 2011). Models have simple representations of groundwater term and dynamics representation may not be adequate to capture long term response and interactions with surface water and ecosystems:

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
			been developed: AWRA-R, a river network model (Band, 2011).	further R&D required (Band, 2011).
Improved characterization of ground-surface water connectivity	Groundwater dependent ecosystems	S-MsC	**Floodplain:** - MODIS time-series indices (EVI and NDMI) to generate probabilities of terrestrial vegetation dependent on ground water sources over past 10 years (250 m res) and annual patterns of terrestrial vegetation likely dependent on ground water sources (250 m res; H. Hemakumara/M. Mitchell, NOW; Mitchell *et al*., 2010).	**Floodplain:** - Potential for improvement of MODIS method through integration of land surface temperature, soil moisture modelling, water table mapping, field work and validation using Landsat imagery (NOW, 2012).
Monitoring of groundwater levels and use outside of currently monitored areas	Groundwater level	Gr	**Basin:** - Use of GRACE to detect hydrological change (Leblanc *et al*. 2009) at coarse scale (>300 km). Mass change is the total water storage (TWS) changes, including contribution from surface water, soil moisture and groundwater aquifers (Doubkova *et al*. 2011). Groundwater estimates can be derived by subtracting soil and surface water components from GRACE TWS. - Use of GRACE products (CSR and GRGS) and modelled soil moisture to derive estimates of groundwater storage changes (Tregoning *et al*. 2012)	- Further research into how GRACE can be assimilated into hydrological models for Australia (Tregoning *et al*. 2012). Modelling of error needs attention. Greatest uncertainty arises from separation of soil moisture and groundwater. Extensive ground data required.

Table 6.5 The usefulness of remote sensing for measuring key variables associated with catchment disturbance, as related to MDBA business and information needs (Source: adapted from CSIRO, 2003; Alluvium Consulting, 2011).

MDBA information need	**Metric**	**Recommended and complementary data sources**	**Operational Australian examples**	**Opportunities**
Land cover, land-use and land management	Baseline and annual land cover/land use (LCLU)	S-MsM S-MsF, A-Ms, SAR	**Basin:** - VIC DPI: VIC Land Use Information System (Morse-McNabb, 2011) – project to produce annual state-wide maps of land tenure, land use and land cover. Land tenure is derived from VIC Govt GIS information. Land use is derived from value-general data. Land cover is derived from remotely sensed data (MODIS MOD13Q1 EVI product). Land cover is initially produced at 250 m resolution, while the final product (all 3 layers) is generated on a property parcel basis for the state. The work aligns with National Land Cover Mapping Program. - QLD Land Use Mapping Program (QLUMP): catchment scale mapping combining state cadastre, public land databases, satellite data (Landsat TM/ETM+, SPOT-5, Quickbird, aerial photography), ancillary data and field survey (ABARES, 2011). - National land use mapping for Australia: Years: 1993, 1995, 1997, 1996, 2000 and 2002. Scale 1:2,500,000 (http://www.brs.gov.au; Stewart *et al*. 2001). - Country-wide LCLU maps based on time-series processing of Landsat archive, as part of Australia's National Carbon Accounting System (NCAS; AGO, 2002, Furby *et al*. 2008). - Time-series LCLU maps derived from ALOS PALSAR data for Tasmania (Mitchell *et al*. 2012).	**Site and reach:** - High resolution MS data now widely available, but should only be used after change has been flagged and in associated with field visits (P. Carlile, MDBA). **Floodplain:** - SPOT 15 m MS images or similar to be used where flagging indicates change has occurred (P. Carlile). **Valley:** - Landsat ETM+ or equivalent, possibly acquired at key seasonal change dates or after some major event (e.g., flood; P. Carlile). Mapping approach depends on land cover/land use in different agricultural regions and type of land management. - Potential of data fusion of optical and SAR data at equivalent spatial resolution (P. Carlile). - Flagging change for examination with higher resolution imagery or in the field (P. Carlile). **Basin:** - MODIS global land cover product (1 km), derived by supervised classification using global training database interpreted from high resolution imagery and ancillary data. Realistic classes global scale, good performance at regional scale. Addition of longer time-series will improve quality of MODIS product (Friedl *et al*. 2002).
	Land cover/land use change (LCLUC)	S-MsM S-MsF, S-MsC, SAR	**Basin:** - VIC Land Use Information System generates LCLU data on an annual basis, providing the potential for assessing and monitoring trends and changes in LULC (Morse-McNabb, 2011). - National Dynamic Land Cover Mapping project: based on time-series MODIS EVI over 2000-2008, useful for assessing change in LC dynamics in response to human/natural change (Lymburner *et al*. 2011).	**Basin:** - Low resolution image data, e.g., NOAA AVHRR or similar to monitor change on regional basis. Excellent for showing change due to drought or flood conditions (e.g., NDVI; P. Carlile, MDBA). - NOAA undertakes similar world-wide study. Data can be obtained cheaply on a daily basis; fused images can eliminate cloud problems, and give a monthly or even weekly overview. One of main benefits is flagging of

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
			- Country-wide LCLU change maps based on time-series processing of Landsat archive, as part of Australia's National Carbon Accounting System (NCAS; AGO, 2002, Furby *et al*. 2008). - National Forest Trend (NFT) data generated using Landsat time-series woodiness index. Approx. timing, direction, magnitude and spatial extent of changes in vegetation are shown. Subtle changes in forest density are detected (Lehmann *et al*. 2012). - Time-series LCLU change maps derived from ALOS PALSAR data for Tasmania (Mitchell *et al*. 2012).	change for further analysis at higher resolution (P. Carlile). - Global Vegetative Cover Conversion (VCC) product derived from MODIS 250 m data. Provides alert to land cover change from anthropogenic activities and extreme natural events (Zhan *et al*. 2002).
	Hardwood and softwood plantation	S-MsM S-MsF, SAR	**Basin:** - National Plantation Inventory (NPI), BRS. Australia-wide mapping for year 2000, based on 250 m grid (http://www.brs.gov.au) - Identification and mapping of hardwood (eucalyptus) and softwood (pinus) plantation in young regrowth, intermediate and mature stages, and change mapping (deforestation and regeneration) in Tasmania using L- and C-band SAR (Mitchell *et al*. 2012).	
	Landscape Development Index (LDI)	AP, A-Ms, S-MsF, S-MsM		**Basin:** - Quantitative measure of the intensity of human use of landscapes. Scales the intensity of activity based on non-renewable energy use. Uses land cover/land use data and energy use per unit area to estimate potential impacts from human dominated activities. Can be used to determine buffer distances between human landscapes and sensitive wetlands (Brown and Vivas, 2005).
Vegetation extent, type and condition to inform changes in interception and fire risk associated with water reform	Fuel load	ALS, A-Ms, A-Hs	- Comparison of field assessments of fuel load and vegetation indices (e.g., NDVI) extracted from HyMap and Daedalus 1268 ATM data. Relative fire risk mapped using HyMap derived fuel load and anthocyanin content, and DEM derived slope and aspect (Taylor and Roff, 2008). Canopy closure (and species) is limiting to degree of correlation between field-based fuel load and NDVI. Scaling plot measurements. Positional accuracy of sample plots.	- Exploit synergy between LiDAR return and HyMap spectral data. - Model based approaches that combine DEMs, vegetation type and indices, and textural variance for improved fuel loads. - Use of future hyperspectral satellite data. - Regression between ALS and field derived coarse woody debris (CSW; Aardt *et al*. 2011).

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
	Burnt area	S-MsC, SAR		**Basin:** - Bi-directional reflectance (BRDF) model inverted against multi-temporal MODIS 500 m land surface reflectance observations to map burned areas. Results validated against MODIS active fire product. Algorithm maps the location and approx. day of burning (Roy *et al*. 2002). - Research into applicability of algorithm to MODIS 250 m data (Roy *et al*. 2002). - MODIS fire products, including global daily fire product. Algorithm uses brightness temperatures from MODIS 4 and 11 µm channels. Validated using ASTER data, acquired simultaneously with MODIS. Available from Earth Resources Observation Systems Data Centre (EDC) Distributed Active Archive centre (DAAC). MODIS Rapid Response System developed to provide fire data to agencies within a few hours of acquisition for strategic fire management (Justice *et al*. 2002).
Mapping of vegetation extent, type and condition to inform groundwater models	Forest cover and extent	AP, ALS, S-MsC, S-MsM, S-MsF, SAR	**Floodplain/basin:** - Routine production of Landsat TM/ETM+ derived foliage projective cover (FPC) for mapping woody vegetation and change (QLD SLATS program, http://www.derm.qld.gov.au/slats/). LiDAR used to validate model predictions of FPC (Armston *et al*. 2009). - QLD SLATS approach adapted to NSW SPOT-5 data for high resolution woody vegetation mapping (Hicks, 2012). SPOT FPC derived by cross-calibration with Landsat FPC. Landsat data is calibrated for QLD, and SPOT results have not been validated. **Basin:** - National Forest Inventory (NFI) 2003, based on 250 m grid. - Continental Forest Monitoring Framework (CFMF): extension of NFI. Nationally consistent baseline forest cover and trend information. Multi-scale approach using fine and coarse resolution RS data and field plots (Wood *et al*. 2006).	**Floodplain:** - Landsat derived regrowth, thinning and woody thickening (QLD SLATS). - Use of vegetation indices derived from optical data (Lucas *et al*. 2000). - Use of allometrics equations and scaling factors from LiDAR data (Lefsky *et al*. 2002). - Use of SAR intensity, texture and tone (Mitchell *et al*. 2012). - Integration of RS data (Vaglio Laurin *et al*. 2013). **Basin:** - Global land cover from MODIS (Friedl *et al*. 2002; USGS 2012). - Time-series analysis of multi-resolution optical (Hansen *et al*. 2010; Broich *et al*. 2011) and Landsat ETM+ (Potapov *et al*. 2012) data for quantifying forest cover loss. - Spectral vegetation indices for monitoring forest states and canopy processes (Huete, 2012).

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
	🟩		- Country-wide forest extent maps based on time-series processing of Landsat archive, as part of Australia's National Carbon Accounting System (NCAS; AGO, 2002, Furby *et al*. 2008). - Time-series forest/non-forest maps derived from ALOS PALSAR data for Tasmania (2007-2010). F/NF also derived using RADARSAT-2 data from 2009 (Mitchell *et al*. 2012).	
	Species composition (Jones *et al.,* 2013)	AP, A-Hs, ALS, S-MsM, S-MsC	**Site/reach and floodplain:** - Use of aerial photography, CASI and HyMap data to delineate and classify individual tree crowns, QLD (Lucas *et al*. 2008). Species must be spectrally distinct. High cost of high res airborne hyperspectral data. - Air photo interpretation (API; Tickle *et al*. 2006). API is labour-intensive, subjective, limited in spatial coverage and incurs large data volumes.	**Site/reach:** - Integration of hyperspectral and LiDAR height data to map forest species (Dalponte *et al*. 2008). - Use of LiDAR derived crown shape and intensity to map tree species (Kim *et al*. 2009; Orka *et al*. 2009). Small footprint LiDAR seldom available over large areas. **Basin:** - Multi-temporal SPOT-4 VEGETATION data used to map forest types (Xiao *et al*. 2002). - Integration of satellite and ancillary data, e.g., MODIS products and elevation, soil and climate data to map forest type at 250 m (Ruefenacht *et al*. 2008). - Use of Landsat data to map forest types (Helmer *et al*. 2012).
	Vegetation communities/associations	S-MsF S-MsM, A-Ms, AP, ALS	**Basin:** - NSW OEH Plant community Type (PCT) mapping using time-series SPOT-5 data (Denholm *et al*. 2012). Object-based, unsupervised classification and validation using ADS40/80 and SPOT-5 imagery. Attribution using species distribution models and floristic survey (plot) data. Opportunistic capture of SPOT-5 data. Seasonal effects and cloud cover can be limiting. Substantial and high-speed data storage required. Gaps exist where field survey and records are absent or poorly sampled. - SPOT-5 approach applied to map approx. 35,000 km^2 of Murray CMA, including 100 vegetation classes (A. Roff, OEH). - VIC DSE Ecological Vegetation Class (EVC) mapping of	**Basin:** - High resolution vegetation type map to be produced high resolution imagery (LiDAR, RapidEye and SPOT) acquired for VIC Rivers and LiDAR project. Model based ECV mapping at catchment scale will incorporate new spatial layers (e.g., fAPAR and LAI) derived for woody vegetation.

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
			native vegetation. Model approach using time-series Landsat imagery, ancillary data and field survey (VIC DSE, 2007). Dataset is limited by scale at which produced, and inclusion of significantly altered or poorly predicted native vegetation. - QLD Regional Ecosystems (RE) mapping based on hierarchical classification system using bioregions, land zones, vegetation association or variation in geology/landforms/soils within a land zone (Neldner *et al*. 2012). Pre-clearing RE maps derived from air photo interpretation and manual digitising. Remnant extent mapping derived from interpretation of Landsat TM, SPOT, aerial photography and field survey. Remnant/non-remnant status determined by comparison with reference sites. - SA regional native vegetation extent mapping using Landsat TM imagery, aerial photography and field survey data (DEH, 2006). Vegetation is described according to National Vegetation Information System (NVIS). Polygons attributed with extent, vegetation type, structure, dominant species and stratum characteristics. - National Vegetation Information System (NVIS): Present day and pre-European vegetation mapping, varies in scale (1: 5,000-1:1,000,000). (http://environment.gov.au/erin/nvis/index.html) - Integrated Vegetation Cover: most comprehensive dataset as compiled from other vegetation datasets, complete coverage of Australia, 100 m grid (Thackway *et al*. 2004).	
	Wetland type	S-MsM, S-MsF, SAR	**Basin:** - Broadscale mapping of NSW wetlands undertaken using time-series (1975-1998) Landsat TM and MSS imagery. Unsupervised classification and iterative reclassing to resolve ambiguous classes. Unable to distinguish palustrine and lacustrine wetlands (Kingsford *et al*. 2004). - Systematic mapping of mangrove and saltmarsh in	**Floodplain:** - Landsat imagery used to map small playa lakes and investigate environmental change (Castaneda *et al*. 2005). Visual interpretation, colour transforms, principal components analysis, and unsupervised classification used to map 5 thematic classes (water, watery ground, wet ground, vegetated ground, dry bare ground).

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
			South Australia. Regional scale wetland inventories are field based, augmented by aerial photography, topographic mapping and satellite imagery. - Detailed habitat mapping of Coorong and Lower Lakes, SA, using aerial photography, ancillary layers and field survey data (DEWNR, 2012). - QLD Wetlands Program: state-wide wetland mapping using existing mapping (Landsat water bodies), RE mapping, topography and springs database. High resolution (SPOT, aerial photographs) and ancillary data used to attribute and assess products (EPA, 2005). Product will be improved with new field survey data, and improved/updated water body and drainage layers. - Landsat TM/ETM+ imagery from 1999-2011 used to derive spatially and temporally explicit surface water body extent on Swan Coastal Plain, W. Australia (Tulbure and Broich, 2013). - Image transforms applied to multi-date PALSAR imagery to discriminate open water, edge wetland, inundated floodplain, other forest, grassland etc. in Macquarie Marshes (Milne *et al*. 2008).	Feature detection dependent on scale of imagery. Features must be spectrally distinct. Periodic ground data is essential. - Rule based classification of Okavango swamp, Botswana, using spectral (Landsat, AVHRR, ATSR) contextual and digitised features (McCarthy *et al*. 2005). - Object based classification of Landsat ETM+ Pan imagery, 15 m resolution, to map temporal changes and extents of wetland types in Tanzania. Detection of similar classes improved by addition of shape, size, proximity and association attributes (Canisius *et al*. 2011). - ALOS Kyoto and Carbon Initiative Wetlands Products: global wetland extent and properties, seasonal monitoring of major wetland regions, and mapping and monitoring of key wetland functional types (Lucas *et al*. 2011).
	Ground cover	S-MsM, S-MsC	**Site/Reach and floodplain:** - Mapping fractional ground cover (fractions of green veg, dead/brown veg and bare ground) using Landsat imagery (Abuzar *et al*. 2008). **Basin:** - Routine generation of Landsat derived fractional cover for QLD (Armston *et al*. 2002; Scarth *et al*. 2010). Constrained unmixing model using field derived end members (Witte and Scarth, 2012). Output shows % bare, green and non-green fractions. - Landsat derived fractional cover with local validation for NSW catchments (Hicks, 2012). - MODIS derived fractional cover for Australia (Guerschman *et al*. 2009a).	**Basin:** - National annual fractional cover product to be generated by GA.
	Forest canopy height (Jones *et al*., 2013)	ALS, SAR, InSAR	**Site/reach and floodplain:** - Various approaches to height estimation using ALS	**Site/reach and floodplain:** - Use of LiDAR to derive multi-scale canopy height

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
			(Goodwin *et al*. 2006; Lee and Lucas, 2007; Jenkins, 2012). Scaling issues from plot to stand. High cost of ALS over extensive areas. - Landsat FPC used to adjust ALOS PALSAR backscatter, from which tree height is retrieved (Clewley *et al*. 2010). **Basin:** - ICESat GLAS used to assess canopy height at continental scale (Lee *et al*. 2009).	estimates (Lim *et al*. 2003; Wulder *et al*. 2008). - Use of LiDAR, radar and field measurements to estimate canopy height (Sexton *et al*. 2009). **Basin:** - Future elevation data from IceSAT-2. - Future SARs and Polarimetric interferometry (PolInSAR) techniques. - Use of TanDEM-X DEM for canopy height modelling (Kugler *et al*. 2011). - Tree height estimation using dual frequency (X- and P-band) airborne interferometric GeoSAR data (Williams and Jenkins, 2009).
	Stand volume (Jones *et al.,* 2013)	ALS S-MsF, SAR	**Site/reach:** - Stand volume estimate for pine plantation using ALS (Turner *et al*. 2011).	**Site/reach:** - Empirical relationships established between LiDAR point cloud metrics and field data (Holmgren, 2004; Yu *et al*. 2010). - Use of high resolution satellite optical data and derived texture metrics for estimating structural parameters (Ozdemir and Karnieli, 2011; Gomez *et al*., 2012).
	Basal area (Jones *et al.,* 2013)	ALS	**Site/reach:** - Use of LiDAR to predict basal area using 50th height percentile and intensity data (Haywood and Stone, 2011)	
	Stem density (Jones *et al.,* 2013)	ALS S-MsF, SAR	**Site/reach:** - Landsat FPC used to adjust ALOS PALSAR backscatter, from which stem density is retrieved (Clewley *et al*. 2010). - Use of LiDAR to identify individual trees (Lee and Lucas, 2007; Turner *et al*. 2011; Musk, 2011; Kandel *et al*. 2011). Difficult to estimate in complex forest.	**Site/reach:** - Use of LiDAR to identify individual trees (Persson *et al*. 2002). - Statistical distribution-based methods from LiDAR metrics (Naesset and Bjerknes, 2001). - Textural metrics from optical data (Klobucar *et al*. 2011; Ozdemir and Karnieli, 2011).
	Vertical structure (Jones *et al.,* 2013)	ALS, AP, SAR	**Site/reach:** - Vertical structure determination using stereo photogrammetry (Fensham *et al*. 2002) and ALS (Lovell *et al*. 2003; Lee *et al*. 2004; Lee and Lucas, 2007; Miura and Jones, 2010; Jaskierniak *et al*. 2011).	**Site/reach:** - Vertical structure determination using terrestrial LiDAR (Parker *et al*. 2004), ALS (Means *et al*. 1999) and radar (Hyyppa *et al*. 2000).
	Leaf Area Index (LAI) (Jones *et al.,* 2013)	ALS, S-MsC	**Site/reach and floodplain:** - Estimation at regional scale using LiDAR (Armston *et*	**Floodplain:** - Estimation at regional scale using LiDAR (Zhao and

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
	🟩		*al*. 2012). Direct ground measurement: high accuracy but inefficient (time and labour intensive). Indirect methods are more suitable for large-scale estimates.	Popescu, 2009). **Basin:** - Global scale monitoring of LAI using MODIS (Knyazikhin *et al*. 1998), CYCLOPES and GLOBCARBON (Gobron and Verstraete, 2009). Accuracy dependent on spatial and temporal qualities of RS data
	🟩 Fraction absorbed of photosynthetically active radiation (fAPAR)	S-MsC		**Basin:** - 19-year AVHRR data (1982-2000) used to characterise major ecosystem disturbance events/regimes at 8 km spatial resolution over North America. Potential disturbance is identified through anomalously low fAPAR values that persist >1 year in any pixel. Best detection where major loss of biomass. Results links to numerous disturbances, e.g., cold and heat waves, forest fires, tropical storms and large-scale logging (Potter *et al*. 2005). Coarse resolution limits detection of small-scale and selective logging, wildfires <6,400 ha, localised flooding, and impact of ice/wind storms (Potter *et al*. 2005).
	🟨 Forest biomass and carbon	ALS, SAR, S-MsM	**Site/reach and floodplain:** - Direct estimation from LiDAR metrics (Lucas *et al*. 2006). - Landsat FPC used to adjust ALOS PALSAR backscatter, from which stem height and density are retrieved. AGB then estimated using allometric equations (Clewley *et al*. 2010). - Empirical relationships between total above ground biomass (AGB) and SAR (Lucas *et al*. 2010). Often limited ground observations are available. Allometrics might not be available for particular species. - Relationships between Landsat derived FPC and basal area and AGB (Henry *et al*. 2002). **Basin:** - Empirical relationships between coarse resolution satellite data and AGB (Berry and Roderick, 2006). - Integration of Landsat derived LCLU and change	- Future SAR satellite launches (e.g., BIOMASS).

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
			maps, meteorological data, soil type and carbon, and land management info in Full Carbon Accounting model (FullCAM) to estimate greenhouse emissions arising from anthropogenic activity. Part of Australia's National Carbon Accounting System (NCAS; AGO, 2002, Furby *et al*. 2008).	
	Regrowth stage	SAR S-MsM	**Floodplain:** - Three regrowth stages (early, intermediate and remnant) mapped in Brigalow Belt, QLD, through integration of ALOS PALSAR and Landsat FPC. Field plots were assigned a regrowth stage based on height and cover relative to undisturbed stands. Image data segmented and each object is assigned a growth stage by comparing backscatter and FPC to reference distributions. Overall accuracy >70 %, increasing to 90 % when intermediate regrowth was excluded (Clewley *et al*. 2012).	

Table 6.6 The usefulness of remote sensing for measuring key variables associated with socio-economic indicators, as related to MDBA business and information needs (Source: adapted from CSIRO, 2003; Alluvium Consulting, 2011).

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
Changes in irrigated and non-irrigated cropping over time for: Basin wide estimation of irrigation water use	🟩 Irrigated and non-irrigated crops	S-MsM, S-MsC, SAR, AP	**Floodplain:** - Multi-temporal Landsat ETM+ panchromatic data used to extract information on seasonal land use/land cover to investigate agricultural water use (Canisius *et al*. 2011). Acquisition of cloud-free images for LULC mapping. **Basin:** - Australian Irrigated Areas v1A: national scale mapping of actual irrigation areas based on interpretation of aerial photography, and moderate-coarse scale satellite imagery (NLWRA, 2001). - VIC DPI – VIC Land Use Information System data, perennial/annual pasture mapping and data derived from ET projects could contribute to this goal.	**Site/reach:** - Relatively straightforward and mostly a resource issue to do (J. Walker). - LU maps could be used to identify typical water use profiles at paddock scale, with an additional identifier as to whether it is dryland or irrigated crop – possibly identify using thermal infrared and day/night differences (J. Walker). - Based on knowledge of dry/irrigated paddocks and crop type, rough water budgets could be calculated at farm, catchment and basin scale to compare against other estimates such as water orders (J. Walker). - Better data on precipitation would be hugely beneficial to water balance modelling studies. In addition to weather radar and other satellites, there is also potential to measure this through attenuation of between-tower cell phone signals (J. Walker). **Floodplain:** - Depending on irrigation method, this could be assessed using spaceborne L-band radar, but not after rain. Areas with higher moisture content will show up clearly compared to dryer areas (P. Carlile, MDBA).
Changes in irrigated and non-irrigated cropping over time for: Assessing and predicting the impacts of the Basin Plan on the seasonal and annual cropping systems	🟨 Irrigation frequency	S-MsC, S-MsM, SAR	**Site/reach:** - Use of remote sensing for law enforcement. High frequency (ideally every 14 days or less) MODIS used to detect areas of land that have had water applied to identify potential unlawful take of water. Use of imagery is not intended as evidence. Imagery will be used for intelligence purposes to target suspect properties for on-ground compliance inspections (C. Jones, NOW). **Basin:**	**Site/reach:** - Thermal infrared and/or remotely sensed ET data could be used to identify irrigation frequency (J. Walker). - Additional spot audits could be conducted through targeted airborne spectral and microwave (for soil moisture) data captures, by upgrading existing national airborne mapping capability (J. Walker). - Information on vegetation health from remotely

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
	🟨		- VIC DPI – VIC Land Use Information System data, perennial/annual pasture mapping and data derived from ET projects could contribute to this goal.	sensed estimates of LAI, crop yield etc. could be used to monitor outcomes from changes in water use; this could be linked to on-farm crop yield measurements from proximal sensors on harvesters etc. (J. Walker). - Remotely sensed vegetation data could also be linked to water/crop modelling systems that predict crop/water status and are updated through model-data fusion/assimilation when crop and soil moisture status observations are available (J. Walker). **Floodplain:** - Use of spaceborne SAR, but not after rain (P. Carlile, MDBA).
Changes in irrigated and non-irrigated cropping over time for: Assessing and predicting seasonal changes in cropping and changing socio-economics at the valley scale	Seasonal changes in crop type	S-MsM, SAR	**Floodplain:** - Mapping perennial and annual pastures using Landsat imagery (Abuzar *et al*. 2008). - QLD DERM developing methods for crop frequency monitoring using timer-series Landsat and ALOS PALSAR data. Assessment of crop structure (height, mid-storey and age class), change in persistent green and distribution of bare ground (Witte and Scarth, 2012).	
Changes in irrigated and non-irrigated cropping over time for: Detecting potential seasonal over abstraction by irrigators	Over-abstraction of water	S-MsC	- Coarse resolution optical imagery used for desktop investigations to compare volume of water used with volume of water metered. This information would be used to identify high risk properties for closer monitoring (C. Jones, NOW).	

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
Changes in basin developments, infrastructure and assets	Farm storages, bores, levees, plantations, floodplain harvesting infrastructure, plants, industries to assist with WSP development, and development proposals	AP, S-MsM, S-MsF	**Site/reach and floodplain:** - High resolution digital imagery (ADS40, 50 cm) complemented by SPOT-5 to map structures and storages in Macquarie Marshes and other wetlands, and farm dams on a local scale (M. Shaikh, NOW; Shaikh *et al*. 2011). - Farm dam development mapped using high resolution aerial photography (Kim *et al*. 2007). **Basin:** - In 2007, GA mapped man-made water bodies including farm dams for approx. half of MDB. New baseline mapping using 2005 high resolution imagery (SPOT-5) and historic Landsat imagery to quantify changes in farm dams and to map spatial extent. Validation using derived vegetation and water indices, and visual interpretation of SPOT imagery. Mapping accuracy estimated at >95 %. Results demonstrate an increase of 6 % in total number of dams over 10-year period, and highly localised nature of change which may have had significant impact on local stream flow (MDBC, 2008). Detection dependent on size of feature and spatial resolution. Clustering of dams in rural residential areas makes them difficult to detect using Landsat. Mapping errors due to misinterpretation of imagery (e.g., black soil and shadows). - Time-series Landsat-5/-7 data acquired between 1987-2009 used to map water bodies in QLD. Classification based on thresholding a standardised multiple regression water index. Outputs were combined to produce the mean extent for all years and an estimate of persistence (DERM, 2010). Only dams larger than 1,875 m^2 were mapped. Smaller dams may be mapped in future project.	**Site/reach:** - Depending on size, could be flagged using Landsat ETM+. Some of these assets can only be acquired with 1 – 2 m resolution data, which would be at high cost (P. Carlile, MDBA). - Ongoing monitoring of farm dams should form part of an integrated land cover monitoring program and undertaken routinely at a range of spatial/temporal scales. Inclusion of high resolution imagery to update mapping at large-scale. Use future imagery acquired in non-drought conditions and classify changes in surface water extent (MDBC, 2008).
Clearly linking socio-economic changes to water reform through: the	Potential indicators: Land use, length of sealed roads in towns, condition of sporting grounds, number of vacant houses,	A-Ms, S-MsM, SAR		**Site/reach:** - Airborne thermal (10 m) and Landsat-8 (60 m) thermal band. - Landsat (100 m) possibly used every year.

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
identification of predictor variables	factories, silos, processing plant activity, changes in transport hubs within basin. Also built vs. non-built structures, new development, new roads			- ADS40 (50 cm) possibly used to measure town expansion over 5 years. - UAV is used in China to look at population centres (safety, cost – thermal cameras)- Monitor towns on a yearly basis with 1 – 2 m resolution data, preferably not in dry season, and use NDVI type index but with built structures being the non-veg component rather than soils. Change will indicate some measure of growth and changed socio-economic circumstances (P. Carlile, MDBA).

Table 6.7 The usefulness of remote sensing for measuring key variables associated with environmental flows, as related to MDBA business and information needs (Source: adapted from CSIRO, 2003; Alluvium Consulting, 2011).

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
Antecedent catchment and floodplain conditions	Soil moisture	S-Pr, SAR	**Basin:** - Daily satellite derived top soil moisture products from passive (Windsat, AMSR-E and SMOS, 1978-2018; Draper *et al*. 2009) and active (ERS, Metop ASCAT, 1991-2020) microwave sensors (L. Renzullo, CSIRO). - Assimilation of satellite derived estimates with water balance models to arrive at best informed antecedent basin conditions (WIRADA Project, 2008-2013; L. Renzullo, CSIRO). - Australia wide application with experimental testing in Murrumbidgee catchment, NSW, WIRADA project (Renzullo *et al*. 2012). Coarse resolution satellite data (25 – 50 km) and data assimilation computational cost (L. Renzullo, CSIRO). Extensive ground calibration required. Decoupling effects of vegetation and surface roughness requires complex modelling. - Integration of PLMR (radiometer) and airborne L-	**Basin:** - Future use of SMAP (Kim *et al*. 2012) and SAOCOM (Frulla *et al*. 2011) data for soil moisture estimation. - Daily satellite derived top soil moisture products from passive radar (Windsat, AMSR-E and SMOS, 1978-2018; Wigneron *et al*. 2007; Kerr *et al*. 2006). - Combination of SAR backscatter and forward modelling to estimate soil moisture (Moran *et al*. 2005).

MDBA information need	Metric	Recommended and complementary data sources	Operational Australian examples	Opportunities
			band SAR (PLIS) for soil moisture estimation, SMAPEX-3 field experiments in Murrumbidgee catchment (Monerris *et al.,* 2011).	
Improved measurement of releases and abstractions from storages and river channels	Water height , depth, extent	ALS, ALB S-Ra, A-Hs, S-MsF, S-MsM	**Floodplain and Valley:** - Combination of ALB and multi-beam echo sounder (QLD Government, 2012). Cloudy/turbid and very shallow water affects ALB measurement - Integration of ALB and ALS for deriving high resolution DEM and water height measurement (Quadros *et al*., 2008; Sinclair & Quadros, 2010; Austin & Gallant, 2010). Poor integration of terrain height acquired by ALS and water depth collected by ALB - Use of satellite radar altimeter Jason-2/OSTM (2002-2020) to measure water height in large (>1 km) storage tanks within ±30 cm accuracy in near real time (Gouweleeuw *et al*. 2011). Storage size (>1 km) and limited satellite track coverage (>300 km apart), 10 day frequency.	**Floodplain and Valley:** - Inland water explicitly targeted in CNES/NASA Surface Water and Ocean Topography (SWOT) mission, scheduled for launch in 2019 (B. Gouweleeuw, CSIRO) - Application of multiple laser and satellite radar altimetry for environmental inundation modelling (Jarihani *et al*. 2012) - Combination of high resolution DEM (e.g., from LiDAR) and flood extent product to estimate water height and volume. - Interpolation of water depths from airborne and satellite imagery (Dekker *et al.,* 2011; Brando *et al.,* 2009; Fugro NPA, 2011; Sagar & Wettle, 2010).

APPENDIX D. MDBA Expert Remote Sensing Workshop, December 2012 - Attendee list

Table 6.8 MDBA Expert Remote Sensing Workshop, December 2012 - Attendee list.

Participant	Organisation	Participant	Organisation
Des Whitfield	DPI, Victoria	Bruce Whitehill	NSW Water
Bill Hirst	ACT Government	Lee Bowling	NSW Water
Peter Scarth	UQ	Paul Carlile	MDBA
Anthony Milne	UNSW/CRC-SI	Mustak Shaikh	NSW Water
Nancy Dahl-Taconi	OEH	Mirela Tulbure	UNSW
Jin Donaldson	MDBA		
Bruce Forster	UNSW		
Arnold Dekker	CSIRO		
Greg Smith	NSW Water		
Linlin Ge	UNSW		
Andy Mcallister	DPI, Victoria		
Lucy Randall	DAFF		
Megan Lewis	Uni Adelaide		
Damian Barrett	CSIRO		
John Trinder	UNSW		
Shaun Cunningham	Monash Uni		
Tim McVicar	CSIRO		
Mark Lound	ABS		
Matthew Miles	SA Gov		
A Zerger	BOM		
Simon Jones	RMIT		
Fraser Macleod	MDBA		
David Bruce	Uni SA		
Richard Hicks	NSW OEH		
Neil Bennett	NSW OEH		
Albert van Dijk	ANU		
R Mount	BOM		
Christian Witte	DERM, QLD		
Sarah Spackman	BOM		
Alister Nairn	ABS		
Andrew Haywood	DSE VIC		
Medhavy Thankappan	GA		
Paul Wilson	DSE VIC		
James Cameron	SA GOV		
Jeff Walker	Monash uni		

APPENDIX E. Key Australian stakeholders

Table 6.9 Key Australian stakeholders (Government, Industry and Academic) engaged in operational and/or R&D programs utilising remote sensing for monitoring of key variables of interest to MDBA.

Variable	NSW	VIC	QLD	SA	ACT
Physical form	**NOW** - Flood inundation modelling and vegetation response mapping	**DPI** - Flood extent mapping	**CSIRO** - Hydrodynamic modelling		**CSIRO** - Open water extent and volume monitoring and hydrodynamic modelling
Water quality	**NOW** - Real time blackwater event monitoring				**CSIRO** - Inland water quality monitoring
Aquatic biota	**NOW** - Integrated Monitoring of Environmental Flows (IMEF) - River Condition Index for monitoring river health - Riparian vegetation extent and condition monitoring	**CSIRO** - Environmental flow monitoring **DSE** - Index of Stream Condition (ISC) for monitoring river health **Monash/DSE** - Vegetation condition mapping, Stand Condition Tool (SCT) **Uni Melb/DWLBC** - Vegetation condition monitoring	**DERM/JRSRP** - Characterisation of riparian vegetation		**MDBA** - Vegetation trends monitoring
Hydrological disturbance	**NOW** - Mapping groundwater dependent terrestrial vegetation	**DPI** - Irrigated crop evapotranspiration (ET) monitoring **Uni Melb/DWLBC** - Water balance and evapotranspiration modelling			**CSIRO** - Modelling evapotranspiration and floodplain harvesting assessment **ANU/CSIRO** - Groundwater estimation
Catchment	**OEH**	**DPI**	**QLUMP**	**DEWNR**	**ABARES**

disturbance	- Plant Community Type mapping - SLATS NSW: woody vegetation change mapping and ground cover monitoring **UNSW/CRC-SI** - Forest, land cover and change mapping, and wetlands characterisation and inundation mapping	- VIC Land Use Information System: annual land tenure, land use and land cover mapping **DSE** - Ecological Vegetation Class (EVC) mapping **RMIT/CRC-SI** - Woody vegetation characterisation **Uni Melb/DWLBC** - Catchment salinity monitoring	- Land use and land use change mapping **DERM/JRSRP** - SLATS woody vegetation and change and ground cover monitoring **UWA/DERM** - Vegetation species, structure and biomass mapping **Herbarium** - Regional Ecosystems (RE) mapping **EPA** - Wetlands mapping	- Native vegetation extent and wetlands habitat mapping	- Australian Collaborative Land Use Mapping Program (ACLUMP) - Australian Land Use and Management classification (ALUM) - National Forest Inventory (NFI) - National Plantation Inventory (NPI) - Catchment salinity monitoring **DSEWPC** - National Vegetation Information System (NVIS) **CSIRO** - National fractional cover **GA** - Dynamic land cover mapping
Socio economic	**NOW** - Mapping farm dams - Irrigation frequency and compliance monitoring	**DPI** - VIC Land Use Information System: pasture mapping	**DERM/JRSRP** - Crop frequency monitoring - Mapping farm dams		**ABARES** - Australian Irrigation Areas: national scale mapping **GA** - Mapping farm dams
Environmental flows		**Monash** - Soil moisture estimation **Uni Melb** Bathymetric survey	**DSITIA** Bathymetric survey		**CSIRO** - Water depth monitoring **CSIRO/BOM** - Australian Water Resources Assessment (AWRA) system