Remote sensing of rivers:

A potential contribution to the Murray-Darling Basin Sustainable Rivers Audit

Final Report by

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For the

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Stephen Wealands[1], Michael Stewardson[1], David Gilvear[2], Jorg Hacker[3], Jeffrey Walker[1], Barbara Downes[1] and Ian Rutherfurd[1]

[1] The University of Melbourne, Australia
[2] University of Stirling, UK
[3] Flinders University, Australia

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Executive summary

Overview of project

Ground surveys are used routinely for surveillance monitoring of rivers across Australia. However, their limitations (e.g. costly, slow, limited sample) are widely acknowledged and airborne remote sensing may provide a cost effective alternative. This technology is largely untried for this application in Australia and although its utility is clearly evident, the accuracy, precision and most productive approach is still uncertain. This project aims to give a realistic appraisal of remote sensing for surveillance monitoring in the Murray-Darling Basin (MDB) as part of the Sustainable Rivers Audit (SRA), with particular focus on evaluating current conditions for two themes of the SRA – physical form and vegetation. The basis for this appraisal is a combination of information garnered from: 1) the findings in the existing literature; and 2) the discussions/outcomes from the workshop conducted on this topic.

The project began with a literature review of the use of remote sensing for river assessments to give the current state-of-the-art from both the scientific and available grey literature (see Appendix 1). This review was provided to participants in the project workshop as background to the study and to ensure the workshop was conducted in an informed manner. Using the review and past reports produced for the MDBC, a list of available satellite and airborne sensors for remote sensing of rivers was compiled (see Appendix 4).

A full-day workshop was held in Melbourne on 29 November 2007, to explore the opportunities of using remote sensing techniques for surveillance monitoring of rivers. The participants at the workshop (see Appendix 5) represented a cross-section of interests and expertise regarding remote sensing of rivers. The workshop focused on taking a realistic view of what is feasible to measure from remote sensing across the Murray-Darling Basin. Participants identified the river metrics they considered ‘feasible’ to measure from remote sensing, before providing details such as the relevant sensors, processing demands and existing examples of use. Then a number of potential solutions were presented and discussed in an open forum to consolidate the general consensus. The two dominant technologies considered necessary in any remote sensing of rivers were: 1) high-resolution imagery (preferably multi-spectral); and 2) LIDAR.

The outcomes of the workshop were discussed extensively amongst the project team and the feasibility of various remote sensing solutions were given preliminary investigation. This included looking at the availability of sensors/operators/imagery within Australia; understanding the potential problems with combining sensors on a single aircraft; and considering logistical issues (i.e. flying height, ground swath covered, spatial/spectral/temporal resolution trade-offs). This report presents an approach for moving forward with remote sensing of rivers for the SRA, considering these various factors and the recommendations of the workshop participants.

Summary of general findings

- Where remote sensing activities are being undertaken by other agencies, the SRA should encourage data collection to be undertaken at spatial resolutions that are compatible with river-focused work (e.g. sub-2.5m) where possible. Inter-agency cooperation will be necessary for undertaking basin-wide remote sensing in a cost-effective manner at this resolution.
- Existing satellite data and derived products are useful for catchment-scale attributes (e.g. catchment vegetation cover), but are not suited to river-scale attributes (e.g. riparian vegetation). The pilot study being undertaken by DSE (for assessing ISC metrics in Victoria) will reveal the suitability of QuickBird and SPOT satellites for this.
- Spatial resolutions of the order of 0.5-1m were suggested as being most suited for SRA metrics, largely due to a reliance on visual interpretation. Visual interpretation was often favoured due to the diversity of river environments in the MDB and the perceived difficulties with obtaining suitable ground truthing data.
- From the list of vegetation and physical form attributes discussed at the workshop, the two data types considered most useful were high-resolution imagery (preferably multi-spectral) and LIDAR. Some other data types were suited to individual metrics, but did not have broad application. Most physical form attributes were dependent on interpreting LIDAR or some other accurate bare-ground representation (e.g. photogrammetric terrain model) that penetrates through the canopy. A high data point density would be required to measure these attributes in smaller streams.

Summary of major recommendations

- The findings of the workshop and review lead us to recommend high-altitude airborne remote sensing using high-resolution digital mapping cameras for capturing imagery suited to the SRA’s needs. High-resolution digital cameras permit large swaths to be covered by single flight lines and can capture multi-spectral information (RGB+NIR) at very high spatial resolutions (e.g. 50cm GSD).

- Workshop participants recognised that multi-spectral information (i.e. 4- to 7-band) was the current playing field for extensive data capture/processing, largely due to long-term availability of Landsat and proven analysis methods. At a minimum, 4-band multi-spectral information was considered necessary for identifying vegetation and mapping vigour. Hyper-spectral information may yield more specialised measures, but the ground truthing requirements make it unsuitable to use across large, diverse spatial extents. This type of information would be of value to collect in any preliminary/pilot study.
- A LIDAR- or photogrammetrically-derived digital terrain model of the river and floodplain is required for measuring physical form attributes accurately. LIDAR is the more promising technology here, although both approaches are degraded by increased vegetation cover near rivers (due to reduced data point density resulting in less detail). The performance of these two approaches must be compared prior to any extensive LIDAR survey, as the potential gains of LIDAR over photogrammetry may be minimal (and thus an unnecessary cost). Existing DEMs were not considered adequate for measuring any of the physical form attributes discussed.
- A high-altitude (e.g. 2000 to 5000m above ground) airborne platform that combines LIDAR with high-resolution multi-spectral digital imagery would be an ideal solution for the SRA, provided that the delivered accuracy is sufficient for measuring attributes. However, such a combination is untried and would require further specification to determine feasibility.
- The workshop suggested that interpretation and processing of this high-resolution imagery at the river-scale is likely to require manual/visual processing for most attributes. The exact tasks/procedures involved are not clearly defined and should be a major focus of any preliminary study. Semi-automated methods are expected to be suited for mapping vegetation extent, vigour and surface water extent, but other automated methods are not considered robust for the environmental variations encountered throughout the MDB.

Plan for moving forward with remote sensing of rivers

- Prior to full-scale implementation of remote sensing in the SRA, an initial phase to the implementation is required to determine survey methods. This phase should focus on the attributes that can be measured from airborne high-resolution multi-spectral imagery (as provided by sensors such as Leica ADS40 or Vexcel UltraCam-D). This should be the focus as it is representative of the data that can be readily collected/processed for large extents (with high positional accuracy and radiometric quality). The study must outline the processing methods to obtain the attributes for the vegetation and physical form themes.

- The initial phase of implementation should also focus on evaluating the additional benefit of LIDAR over photogrammetrically-derived terrain models. To get maximum return/information from additional flights required to capture LIDAR, additional sensors such as a hyper-spectral scanner and thermal imager should be used concurrently, along with the necessary ground surveys for calibrating/verifying the airborne remote sensing. This should be undertaken in a range of river types/styles.
- The initial phase of implementation should:
  - Demonstrate how SRA attributes can be measured from airborne-based assessment, including details of procedures (automated where possible) and some measure of performance/accuracy/representativeness
  - Assess adequacy of airborne photogrammetry for surveying channel and floodplain attributes and evaluate additional benefits of LIDAR
  - Establish surrogates (where possible) for attributes not identifiable in airborne data and/or examine potential for interpolating attributes through regions where the imagery is unsuitable (e.g. shadows, dense vegetation)
  - Recommend how to combine airborne data with ground surveys (and possibly also satellite data for larger-scale attributes) to achieve assessment of river condition at zone and valley-scale (as required by the SRA)
  - Provide sufficient evidence to establish costings for a more extensive implementation
- Some general discussions with the NSW Department of Lands, who operate a government-owned Leica ADS40 from their aircraft in Bathurst, have indicated their interest in supporting an initial phase of implementation using this technology. They are currently undertaking the capture/production of 50cm ortho-imagery throughout NSW and are keen to find multiple users for their data. We recommend pursuing this avenue, along with a complementary airborne sensing mission capturing LIDAR and necessary ground-based sampling support.

Acknowledgements

This report draws from the advice of participants at a workshop held for this project in Melbourne on 29 November 2007. We thank all the participants for their contribution. In addition, advice was provided by David Abernethy and Shane Brunker from NSW Department of Lands; and Frank Rottensteiner and Thomas Weser from the CRC for Spatial Information. Glenn Scholz (S.A. Dept. Water Land and Biodiversity Conservation) reviewed a draft of this report. Laura Vascon, at the School of Enterprise, The University of Melbourne, provided administrative support for the project and its workshop.

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1 Introduction

1.1 Background

Ground surveys are used routinely for surveillance monitoring of rivers across Australia. However their limitations are widely acknowledged. Ground surveys are costly, slow, limited to sites with reasonable access and limited to parameters which can be surveyed rapidly on the ground. Airborne survey may be a cost effective alternative which provides targeted data collection at a fine resolution over great lengths of river. This technology is untried for this application in Australia and although its utility is clearly evident, the accuracy, precision and most productive approach is still uncertain.

The focus of this project is informing surveillance monitoring in the Murray-Darling Basin (MDB) as part of the Sustainable Rivers Audit (SRA), although outputs will inform monitoring for other purposes and rivers. The SRA assesses river condition based on a comparison of current and reference conditions. Reference conditions are determined by modelling the current condition under the hypothetical condition of anthropogenic alteration to the landscape (other than the activities of indigenous Australians which predate European settlement). Current conditions are generally established through ground survey of rivers, although satellite-based data are under consideration for some metrics. This project evaluates the potential contribution of remote sensing, and in particular airborne survey, for surveillance monitoring of river condition. The focus is on contributions to two themes of the SRA - physical form and vegetation – for which remote sensing holds the greatest potential.

In this report, chapter 2 provides a summary of the sensors which have been identified for surveying river metrics of interest to the SRA, and chapter 3 discusses remote sensing solutions for the SRA. These solutions are not costed in detail, due to the many factors that are still poorly defined (e.g. extent of network to measure/map; attributes of most importance; accuracy requirements). If detailed costings are needed, it would be recommended to write a specification (including the spatial extent, spectral bands required, resolution needs, etc.) and request inputs from commercial operators or other suitable providers. Without such information, useful and detailed costings could not be given from providers. An initial implementation in a representative area is the ideal way to learn about these costs and to better compare sensor solutions, although there will also be economies of scale in any basin-wide data acquisition (particularly if shared between agencies).

1.2 Project Tasks

1.2.1 Review of SRA Needs

The project began with a review of the opportunities for remote sensing to contribute the SRA. This review drew on advice from the SRA team at the MDBC, their consultants and available documentation. On the basis of this review, we compiled a list of stream metrics which were (a) of interest to the SRA and (b) could potentially be surveyed remotely. Metrics were assigned a priority level (high, medium or low) based on the feasibility, adequacy and cost of ground observations plus the importance to the SRA. This list formed the basis of the tables in Appendix 2 and 3. Some additional metrics were suggested during the project workshop and have been added to these tables (indicated by an asterix).

1.2.2 Literature review

The existing literature regarding the use of remote sensing for river assessments was reviewed and summarised for all of the project team. This included both the scientific literature and available grey literature (Appendix 1). This review was provided as background to workshop participants. Based on this review and past reports produced for the MDBC, a list of available satellite and airborne sensors for remote sensing of rivers was also compiled (Appendix 4).

1.2.3 Workshop

A workshop was held in Melbourne on 29 November 2007 to explore the opportunities of using remote sensing techniques for surveillance monitoring of rivers. Participants at the workshop (listed in Appendix 5) represented a cross-section of interests and expertise in remote sensing of rivers. The workshop focused on taking a realistic view of what is feasible to measure from remote sensing across the large area that is the Murray-Darling Basin. Initially, a list of attributes relevant to the SRA that were considered ‘feasible’ to measure from remote sensing was compiled. This list was then split into the two major themes – vegetation and physical form – and discussed in more detail to evaluate details of the feasibility. These discussions filled out spreadsheets (collated in Appendices 1 & 2) identifying the relevant sensors, processing demands and existing examples of use. The key themes/solutions raised during discussions are summarised here, along with a list of the SRA attributes that can be measured using the two dominant technologies identified – high-resolution imagery and LIDAR.

2 Attributes of river physical form and vegetation observable using available remote sensing technologies

2.1 Summary of workshop discussion

At the project workshop, it was widely recognised that a ‘census’ type approach was desirable for surveillance monitoring of vegetation. In this approach the vegetation extent and standard measures of vegetation vigour (e.g. NDVI and the derived parameters LAI and FPAR) would be mapped for the whole network. There were two major scales of interest here – the catchment vegetation (i.e. coarser resolution) and the riparian zone vegetation (i.e. interest in finer features). These scales each have different demands on remote sensing as will be discussed. The mapping of extent and vigor would provide the base measures from which other characteristics could be recognised and/or derived. Change detection would be used to recognise something about the physiological status of plants (over time). Vegetation extent mapping could be combined with stream bank mapping to determine changes to microclimate and habitat (e.g. stream shading, bank vegetation). It was also expected that some determination of vegetation structure could be achieved with the addition of detailed height information, but particularly within canopy information. For obtaining more detailed measures of vegetation (or for building indicator/surrogate relationships), detailed site investigations were considered necessary, which would involve a combination of airborne sensing (capturing as much information as possible, including hyper-spectral, thermal, LIDAR).

Discussion of the physical form theme at the project workshop focused on the need for site-based remote sensing. For ‘census’ type variables, such as meander wavelength and channel sinuosity, it was accepted that existing GIS datasets (i.e. cartographically-interpreted from aerial imagery) are sufficient. However, it was noted that the accuracy of the representation could be improved significantly using remote sensing (e.g. representing both banks; using a higher resolution source). The base data requirements for most other variables were either some form of detailed terrain representation (i.e. highly accurate bare ground surface) and high-resolution imagery (for semi-automated or manual interpretation of geomorphic features and physical habitat). The terrain surface (when combined with imagery) would be used for classification of stream types, mapping of floodplain structures, floodplain width and interpretation of channel bankfull width. The imagery could assist with recognizing wetlands and paleochannels, but individually did not help with channel bankfull width. There was also some comment regarding the value of ground-penetrating sensors such as airborne electromagnetics for groundwater and soil attributes, although the spatial resolution is a limiting factor here. Most of the in-stream features (e.g. bed material size, in-stream habitats) were recognised as being possible under optimal conditions (i.e. clear, shallow water; no overhanging vegetation), but unlikely comprehensively across the broader MDB.

There was some discussion in both groups regarding the use of boat-based remote sensing, such as terrestrial LIDAR or SONAR. While these approaches were of potential value, the discussions quickly returned to airborne sensors, due largely to the remoteness of streams in the MDB and the desire to avoid visiting every location on-the-ground to capture this information (as would be required by these other approaches). For site-scale studies, these alternate options may be worth investigating further, to supplement ground-based field work.

2.2 Attributes which can be remotely sensed

Appendix 2 and 3 list the attributes that are considered feasible to measure with available remote sensing technologies. The following sections provide a summary compilation of the information the appendix, focusing on river attributes which are feasible with the different types of sensor. LIDAR and high-resolution imagery (using mainly visual interpretation but some semi-automated methods) are the dominant sensors suggested for measuring or mapping these attributes, but within these two options there are many parameters that must still be defined (and there is some scope for alternatives). The resolution requirements is expected to be of the order of 0.5-1m to meet most SRA needs into the future (and can be down-sampled for a more generalised representation). However, this needs to be reviewed once a decision has been made on the future contribution of remote sensing to the SRA. Issues of spatial resolution will be further clarified by the results from the DSE pilot study looking at the use of SPOT and QuickBird imagery for river assessment. Coarser resolutions (e.g. 2.5-10m) may be sufficient in some cases, although this would need to be evaluated for individual attributes in a range of environmental conditions.

2.3 SRA attributes for which high-resolution imagery is required

- Channel sinuosity and meander wavelength – if new stream bank data is to be collected
- Geomorphic stream type – using visual classification/inspection and fuzzy classification
- Paleochannels – particularly if they contain water
- Bed material size – assuming exposed sediments and no overhanging vegetation
- Large woody debris – assuming clear enough view through the canopy
- Structures on the floodplain – combined with LIDAR for optimal recognition
- In-stream geomorphic units and physical habitats – assuming no shading/overhang
- Permanency of wetlands – may not require high-resolution, depending on wetland size
- Vegetation dependency on groundwater – indicators from NIR band
- Vegetation extent and derived measures of composition – classification and calculation
- Area covered by different vegetation groups – classification of multiple bands
- Surrogates for tree canopy vigour – band combination and calculation
- Provision of habitat – visually recognise small features from imagery
- Stream shading and overhang – combining extent mapping with stream bank definition

2.4 SRA attributes for which LIDAR was considered necessary

- Geomorphic stream type – using visual classification/inspection and fuzzy classification
- Channel bankfull width – measured from LIDAR surface, assuming can define top of bank
- Channel gradient/slope – measured from LIDAR surface
- Bankfull hydraulics – assuming no dense canopy at the top of banks
- Bank angle – assuming no dense canopy at the top of banks
- Active floodplain width – if combined with hydraulic modelling
- Structures on the floodplain – combined with imagery for optimal recognition
- Vegetation canopy structure – combined with imagery to add more detailed attributes

3 Airborne and satellite remote sensing options

3.1 Existing or collected satellite imagery

Various types of remotely-sensed satellite imagery have been collated by State and Federal agencies for a number of mapping initiatives (e.g. land-use/cover and topographic mapping). In particular, SPOT5 imagery (which has 2.5-5m resolution in panchromatic, 10m in multi-spectral) has been (or is being currently) acquired throughout NSW, Queensland and Victoria. However, there can be a lack of temporal consistency with this imagery (i.e. it has a patchwork appearance when mosaicked). While this may be of little consequence to topographic mapping efforts, it causes problems when mapping vegetation and other river characteristics, which depend on temporal consistency. For example, image interpretation for vegetation mapping often uses knowledge of plant phenology to improve vegetation classification. The inconsistency is caused by the fixed schedule of satellite overpasses and the problem of persistent cloud cover in some areas.

Landsat imagery is collected more consistently and used for temporally-sensitive image interpretation, although the spatial resolution is generally considered ‘too coarse’ for investigating riparian vegetation and river characteristics. Landsat has a 30m multi-spectral pixel size, which does not permit clear delineation/classification of riparian zones. As discussed during the workshop, the actual interpretation often requires more than just individual pixel values, making the effective size of a ‘recognisable feature’ 2 or more pixels in size. As such, the SRA should consider putting forward a case for more detailed vegetation mapping efforts that better meet their needs at the riparian zone scale. Initiatives such as the land cover mapping being undertaken in the National Land and Water Resources Audit (National Land & Water Resources Audit 2007) are examples of where the SRA may be able to influence other groups interested in large-extent mapping of vegetation to consider a higher resolution. ALOS and SPOT5 imagery have been suggested as being more suitable for this, although the reduced spectral information relative to Landsat (i.e. 4 bands as opposed to 7 bands) leads to reduced information content and may be a critical factor. For example, SPOT5 may not be sufficient for mapping detailed vegetation groupings, but could be adequate for providing extent and some measure of vegetation vigour. There is a pilot study currently underway (by DSE in Victoria) that is evaluating the usefulness of SPOT5 for riparian vegetation mapping. The findings from this study are expected to be available in early 2008. At present, there is no higher-resolution multi-spectral satellite imagery being collected in

Australia over large spatial extents that we are aware of. Whether SPOT5 is sufficient for mapping stream-side features remains to be seen from pilot studies, but it is unlikely to be useful for small streams.

The existing satellite imagery does not contain complementary, high-accuracy height information, which is necessary for measuring a number of vegetation characteristics and attributes related to the physical form of rivers. The existing options are the SRTM satellite-derived terrain surfaces (30-90m pixel size, RMSE ±5-10m (depending on vegetation cover)) or the existing national 9 second DEM. Neither of these data sources provides adequate detail of vegetation/terrain elevation to assist with measuring the characteristics of interest to the SRA, due largely to their inaccuracy and/or low resolution.

The use of existing satellite data (i.e. the imagery already compiled for large extents) is unlikely to be adequate for the SRA. The spatial resolution of current and planned land use/cover mapping does not address the needs at the riparian zone scale. The temporally-inconsistent collection of these data causes problems with interpreting vegetation attributes and therefore makes any change detection impossible. The base data requirements for vegetation in the SRA suggests that multi-spectral information would be sufficient, thus opening up the possibility of using high-resolution multi-spectral satellites, of which the QuickBird satellite provides the highest available resolution (2.4m in multi-spectral). This sensor is also being evaluated in the DSE pilot study and the findings of this study will be of direct relevance to the SRA. Higher-resolution multi-spectral data is available from airborne sensors, although these often require low-altitude flying heights and therefore narrow swaths (which make covering a river and the associated floodplain in a single pass difficult).

Any efforts made by the SRA to collect a temporally-consistent coverage of the MDB with remotely-sensed imagery should evaluate the ability: 1) to automatically map the vegetation groupings of interest (and the bands required); 2) to detect change between imagery from different times; 3) to combine with a suitable elevation source for interpretation; and 4) to visually recognise the relevant features. This final point is of most direct relevance, as at the simplest level this imagery would be used for visual interpretation and mapping. Most participants at the project workshop had the greatest reliance on manual interpretation for most attributes, with automated or semi-automated methods only being trusted for ‘routine tasks’ (e.g. water delineation, vegetation extent/vigour, unvegetated and urban surfaces). Any data collection efforts with satellite imagery should be undertaken in co-operation with other

State agencies to maximize the potential use of the imagery and to share costs. Other agencies may be interested in more complete coverage, whereas the SRA is expected to be focused on the stream corridor (including floodplain).

3.2 High-resolution multi-spectral airborne imagery

Many of the attributes of interest to the SRA are of very fine scale and determining them from remote sensing requires very high resolution imagery. For example, resolutions of less than 1.0m are likley to be required for visually identifying riverine vegetation types, in-stream features (e.g. large wood) and floodplain structures. With airborne sensing, there is necessarily a trade-off between the swath width and resolution when deciding on the best flying height. Airborne sensors have the ability to capture finer spatial resolutions than satellite sensors because planes can carry the sensors at low altitude. However, covering large extents will usually require multiple flight runs to capture wide swaths (e.g. broad floodplains and meandering valleys).

A new range of airborne digital sensors (e.g. Leica ADS40 or Vexcel UltraCam-D) provide a dramatic increase in resolution for a given swath width. These are beginning to operate in Australia and can alleviate this difficulty with their ability to fly much higher and still capture high resolution imagery (e.g. a flight at 5000m elevation could provide 50cm resolution pixels across a swath 5km wide.). These systems are designed for mapping over large extents and become much more cost effective when doing so. The ADS40 is a ‘satellite-type’ sensor (i.e. push-broom) running from an airborne platform, while the UltraCam-D is a large-format camera. These sensors are operated with both forward and backward look angles and are thus capable of producing photogrammetrically-derived digital surface models (DSM) from the imagery (with high positional accuracy). The ADS40 sensor captures RGB+NIR data at the same resolution as the panchromatic bands, while the UltraCam-D captures the colour and NIR bands at a resolution approximately 3 times lower than the panchromatic (i.e. if panchromatic at 0.5m, RGB+NIR at 1.5m). Therefore, the ADS40 has the capacity to provide the most detailed, digitally-captured and processed imagery available (from a given flying height and with a given swath width).

These sensors appear ideally suited to mapping river corridors, as they combine ultra-high spatial resolution with a sufficiently wide swath, thus being capable of capturing the stream and floodplain in one run (and from much lower altitudes than satellites, thus reducing atmospheric effects and coverage timing issues). In addition to providing high spatial resolution and standard spectral resolution (i.e. RGB+NIR), these cameras have excellent radiometric resolution (12bit), which is of great benefit when observing/classifying details within shadows. Shadows are a major problem in river-based remote sensing and recording greater bit depth is one of the only ways to resolve details in these areas (unless the flying time can be controlled to get optimal sun angles everywhere).

Other airborne sensors, such as hyper-spectral scanners and LIDAR, are typically operated at much lower flying heights to achieve comparable accuracies and thus require multiple flight runs to cover the river corridor. Some more powerful LIDAR instruments (e.g. OpTech Gemini, Leica ALS50) are capable of operating from similar heights to the high-resolution cameras, but there is an accuracy trade-off that may limit the value of LIDAR from these heights. Combining LIDAR with a high-resolution digital camera/scanner is something that requires further investigation and specification to determine feasibility, but could provide an ideal solution for the SRA. There are currently no hyper-spectral or thermal imagers that can achieve comparable accuracies to the high-resolution cameras from high altitudes.

In Australia, the NSW Department of Lands is operating an ADS40 instrument from their aircraft out of Bathurst. This is being used for generating 50cm orthophotos across the state. It is currently being flown to capture 1:100,000 mapping tiles (i.e. an area of 45km x 55km), which each take approximately 1-1.5 days of flying time to capture (under good conditions) (D. Abernethy, NSW Lands, pers. comm.). The SRA may be able to use this mapping and work with NSW Lands to capture data that is ideally suited to their purposes. This imagery contains RGB+NIR and can also be processed to produce DSMs (or bare-earth terrain models with some ‘smart’ processing and selection of surface points below the canopy, as used by many commercial operators). While the processing demands on imagery with such high spatial resolution can be great and more complex, if visual interpretation is to be used the higher resolution available can be of great value. The figure below (from Ehlers et al. 2006) gives an example of the type of imagery available from a high-resolution digital sensor (the HRSC-AX, a pre-cursor to the ADS40). Ehlers et al. (2006) used this type of imagery for automatically classifying change in biotope types and found the high radiometric quality of major benefit when undertaking classification within shadowed areas.

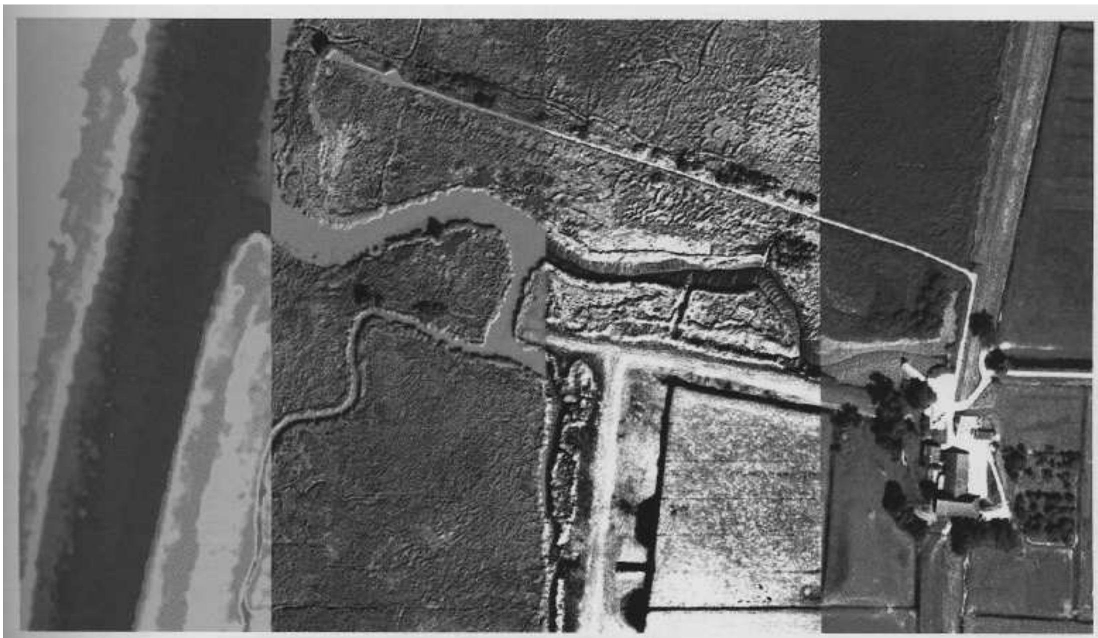

Plate 1. Various views recorded with only one HRSC-AX camera system: digital surface model (DSM) with orange = high elevation, yellow and green = medium elevation, and blue = low elevation; color infrared (CIR); panchromatic; true color (RGB).

3.3 Airborne terrestrial LIDAR

LIDAR information is of particularly value to the physical form theme of the SRA, as it permits detailed physical attributes such as channel bankfull width and channel gradient to be determine remotely (i.e. without field work). LIDAR can also provide a detailed and accurate representation of the entire floodplain, over which hydraulic modelling can be applied to determine other geomorphic measures (e.g. active floodplain width). LIDAR is also considered valuable for understanding characteristics of vegetation structure, due to its ability to penetrate the canopy and provide multiple returns (and even to classify the full-waveform of the LIDAR return). Bathymetric LIDAR also has the potential to measure depths, although this technology is not well developed for river-based work and the algorithms for resolving depth in water of varying turbidity are still being refined. At present, the SRA would be best to limit considerations to airborne terrestrial LIDAR, particularly if considering a large data-collection mission.

As with the high-resolution imagery, LIDAR produces a large amount of detailed information that can be difficult to process and interpret. During the workshop, almost all attributes for which LIDAR was needed were thought to require manual interpretation. If this is the case, then the LIDAR information must be processed into a ‘digestible’ data product, such as a 1m digital terrain (i.e. bare ground) model (DTM) for a human interpreter to view. If the actual data product needed is a 1m DTM (as opposed to a dense point cloud), then there may be trade-offs in the LIDAR collection that could help produce a suitable data product for the SRA (i.e. one that has sufficient accuracy, but also gives a wide swath to avoid multiple runs). As with any airborne sensor, the flying height can be modified to adjust the sampling density (and the accuracy often changes similarly) and this also changes the swath covered. These trade-offs must be considered carefully by the SRA, as flying LIDAR from a greater height may provide the information needed at a suitable resolution (e.g. 1 point per square metre for producing a 1m DTM) while avoiding the need to do multiple runs. For large-extent mapping of the river network, it would be desirable to avoid multiple runs. It may also be useful to just fly the channel using high-precision LIDAR (i.e. one run), while supplementing it with less-precise DSMs (created from high-resolution photogrammetry) or LIDAR from a higher flying height across the broader floodplain.

If undertaking any LIDAR-focused data collection mission, it would be beneficial to fly other complimentary sensors at the same time (as much of the capture cost is in getting the aircraft/equipment in the air). For example, if ADS40 was flown along with coarse resolution LIDAR at 2000m AGL, it could feasibly provide LIDAR data with approximately 0.15m accuracy (and 2m point spacing) and 20cm high-resolution digital orthophotos (RGB+NIR) for a 2km wide swath. This combination would permit the major characteristics identified as being feasible during the workshop to be mapped across the river network, provided that sufficient resources were available for visual and semi-automated interpretation. Additional sensors could also be flown at the same time, such as a hyper-spectral scanner (e.g. CASI1500) or thermal imager (e.g. TASI600). The exact solutions available would depend on the provider and the available equipment, but in all cases the SRA should maximise the sensors running during any flights. The findings from the workshop suggest that some combination of high-resolution imagery and LIDAR for visual interpretation (until better processing techniques emerge) is the most promising solution for the SRA. This could provide a valuable link between the ground-scale field sampling and the broad-scale catchment characteristics that are available from more standard mapping projects (e.g. land use mapping, state-wide DEMs). Without this link, these disparate scales of data that are currently being used will continue to struggle to work with one another.

3.4 Detailed airborne sampling missions

One of the difficulties when discussing the use of remote sensing for rivers is that there are a number of characteristics that are ‘technically feasible’ to measure. These are considered feasible because there are available sensors that, with adequate calibration and ground data/truthing, have been shown to measure the characteristics of interest to adequate accuracy. For example, hyper-spectral scanners are capable of mapping the extent of particular vegetation species, assuming the spectral signature of that species can be clearly defined (and subsequently classified within the imagery). However, when attempting to undertake such measurements across a large extent containing different environmental conditions and in remote areas (where ground control is harder to place), the feasibility of these methods decreases. Therefore, detailed airborne mapping of very specific attributes across large extents is unlikely to be undertaken for the whole MDB. Yet there is still value in testing/piloting such technologies in smaller sample areas or study catchments to evaluate their capability for supporting (or replacing components of) field sampling efforts.

Here we have listed a suite of available sensors that could be used for detailed mapping of physical form and vegetation attributes. If we assume that all these sensors can run co-operatively on a single aircraft at the same flying speed, then we could potentially capture a comprehensive dataset from a flying height of 2000m AGL using:

- Airborne digital imager (e.g. ADS40): ≈0.2m pixels (RGB+NIR) across 2.5km swath (64°)
- Airborne laser scanner (e.g. ALS50): ≈0.15m accuracy, ≈2m spacing, 1.5km swath (40°)
- Hyper-spectral scanner (e.g. CASI1500): ≈1.0m pixels across 1.5km swath (40°)
- Thermal infra-red scanner (e.g. TASI600): ≈2.4m pixels across 1.5km swath (40°)

Such a suite of sensors would permit the majority of SRA attributes listed in Appendices 2 & 3 to be measured/mapped, provided that sufficient ground control, calibration data (e.g. spectral libraries, ground targets) and resources/expertise for processing were available. Unfavourable conditions, such as extensive stream shading and turbidity, will continue to be problematic, but these physical constraints cannot be overcome with exiting technology at the spatial resolution required for many river metrics.

4 Key findings

Inter-agency cooperation

Through involvement with other remote sensing activities being undertaken by other Government departments, the SRA should encourage data collection at spatial scales that adequately represent river attributes (in particular riparian vegetation). Remote sensing endeavours over large extents must involve multiple stakeholders (to share costs) and there is a need to explore opportunities to align the needs of remote sensing for different agencies.

Satellite data

Existing satellite data and derived products are of value for catchment-scale attributes (e.g. catchment vegetation), but are not currently suited to attributes at the river-scale (e.g. riparian vegetation). The adequacy of SPOT5 and QuickBird imagery for this type of work should be garnered from the pilot study that is currently underway for DSE (in relation to ISC attributes).

Required resolution

Most SRA attributes demand high spatial resolution data. Spatial resolutions of the order of 0.5-1m are expected to meet most SRA needs into the future.

Recommended approach

High-altitude (e.g. 5000m AGL) airborne remote sensing using high-resolution digital mapping cameras/sensors (such as the Leica ADS40 or Vexcel UltraCam-D) is suited to the SRA’s needs, while still providing a large swath (which is suitable for covering river corridors) and multi-spectral information at very high spatial resolutions (e.g. 50cm GSD).

Multi-spectral imagery (i.e. RGB+NIR) is the current playing field for extensive data capture/processing. There are reliable and proven surrogates for identifying vegetation and mapping vigour.

Recommended approach

While hyper-spectral data could potentially yield more specialised attributes, the ground control/truthing requirements (e.g. spectral libraries) make it unsuitable for the SRA across large extents. It may, however, be useful for more detailed study of individual sampling sites/reaches (i.e. low-altitude airborne remote sensing). During such detailed studies, other complementary sensors (e.g. thermal imager, LIDAR) could also be flown to provide as much remotely sensed data as possible for the site, although reliable interpretation of additional vegetation attributes is considered difficult.

An accurate representation of the ground surface (e.g. LIDAR) is necessary for measuring physical form attributes adequately. While approximate mapping the channel bank locations may be possible from imagery, most physical form measures demand highly accurate 3D surfaces. LIDAR is likely to be needed in places where vegetation penetration is necessary, but high-resolution photogrammetrically-derived DSMs (such as from high-altitude airborne sensors) may also be suited to this task. These technologies should be compared for determining the physical form attributes before any decision for extensive LIDAR survey is made. Existing DEMs covering large extents were not considered adequate for measuring all the physical form attributes discussed.

Flying LIDAR in combination with a high-resolution digital camera/scanner at an altitude of between 2000 and 5000 m (above ground) could provide an ideal solution for the SRA. However this combination of sensors is untried and requires further investigation and specification to determine feasibility and benefits over flying high-resolution digital camera/scanner alone.

Recommended approach	The interpretation and processing of remotely sensed data at the stream network scale is likely to require manual/visual processing for most attributes. The exact tasks/procedures involved in undertaking this are yet to be clearly defined. Apart from determining vegetation extent, vigour, and surface water extent (and any derived measures from these attributes), semi-automated methods are not considered robust for the environmental variations encountered throughout the MDB.
Next steps	Prior to full-scale implementation of remote sensing in the SRA, a pilot project is required to calibrate the survey methods. This pilot project should focus on the use of airborne high-resolution, multi-spectral data (such as provided by the Leica ADS40 or Vexcel UltraCam-D) as that is the data that is feasible to collect over large extents and suited to the needs of the SRA. The pilot study should also capture LIDAR information for the area of interest to evaluate the capabilities of LIDAR versus DSM for physical form attributes. During such a pilot flight, it would be sensible to also capture thermal and hyper-spectral imagery for use in any future assessments of feasibility. Concurrent ground surveys would be required for verifying (and possibly calibrating) airborne sensing methods in a variety of stream types.

Next steps The initial phase of implementation should be designed to achieve the following goals.

- Demonstrate the capability of airborne-based assessment for SRA metrics.
- Assess the adequacy of airborne photogrammetry for surveying the channel and floodplain metrics required for the physical form theme and evaluate the additional benefits of LIDAR for surveying these metrics.
- For those metrics not identifiable directly from airborne data, attempts should be made to establish surrogate variables which can be identified from the air.
- Examine the potential for interpolation of remotely sensed metrics through regions where features are obscured by canopy, shadow and presence of water.
- Recommend the best approach to combining airborne and ground surveys with the possible addition of satellite data. This requires an understanding of:
    - the trade-off between the accuracy, precision, resolution and coverage, of ground, airborne and satellite survey;
    - the effects of spectral resolution and spatial resolution (i.e. flying height).
- The survey approach should be optimised to achieve assessment of stream condition at the zone and valley-scale.
- Clarify the opportunities to align the needs of the SRA with other agencies involved with remote sensing of environmental conditions within the Murray Darling Basin.
- Establish procedures for processing airborne data to extract the metric of interest to the SRA. Assess the contribution of automatic classification.
- Provide information for a precise costing of implementing Remote Sensing for the SRA throughout the Murray Darling Basin.

Next steps The NSW Department of Lands are operating a Leica ADS40 (i.e. a high-altitude airborne sensor) for producing 50cm multi-spectral orthophotos (and potentially DSMs) for all of NSW. They have been operating this new sensor for 5 months and have shown interest in supporting an initial/pilot study using such equipment. If using data that has already been captured, the costs involved in such a study could be minimal, although new data capture may also be able to work in with their existing flight planning.

We recommend pursuing such a pilot study, supported by additional airborne sensing and ground-based sampling.

References

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Appendix 1: Literature review

Remote sensing of indicators for rivers in the Murray-Darling Basin

Overview

The Sustainable Rivers Audit (SRA) is a program designed to measure the health of the rivers in the Murray-Darling Basin (MDB) at a large-basin scale. It is an initiative of the Murray-Darling Basin Commission (MDBC) and involves partner agencies within each state/territory within the MDB (MDBC 2006). Within the SRA, there are a number of themes, each of which focuses on different characteristics of the rivers/catchments that need to be quantified. This review (and the associated workshop) focuses on how remote sensing technologies can be used to measure indicators required by the Physical Form and Riparian Vegetation/Floodplain Themes of the SRA (MDBC 2003), although some associated indicators from other themes may also be considered and new indicators could be suggested.

At present, these two Themes have a data- and imagery-based assessment undertaken at the valley-scale. The Riparian Vegetation Theme is being assessed using a comparison between 1:100K scale vegetation maps (of pre-1750 conditions) and current SPOT5 imagery. For the Physical Form theme, rivers are being ‘typed’ using attributes derived from best-available DEM analysis (e.g. sinuosity, braiding). These rivers are compared against ‘reference types’ constructed from past parish and country maps (to represent pre-European settlement conditions). While this gives some measure of health at the valley-scale, there remains a need for more detailed and rapid assessment of the SRA indicators at the reach scale. Such assessments would provide complementary information on the condition within each river type or within the different hydro-geomorphic units (e.g. in-channel versus floodplain). The MDBC is also keen to explore other potential indicators that could be measured from remote sensing technologies, particularly pertaining to physical form (F. Bouckaert, MDBC, pers. comm.).

The requirements of these SRA themes are similar to the needs of the Index of Stream Condition (ISC), which is a comparable approach used for Victorian streams by the Department of Sustainability and Environment (DSE) (DSE 2005). Therefore, this review has relevance to both of these monitoring/mapping programs.

The review has been compiled to provide readers with background information on the tasks, technologies and relevant reports/literature pertaining to this topic. It aims to provide the thread that ties many areas of knowledge together, while providing readers with access to more detailed information on the various topics as desired (i.e. the relevant information is not fully summarised here, but it is linked to). Throughout the document, links to the referenced literature (including relevant pages) are provided where possible, so that readers can be well informed on the topic and not just reliant on summaries that often gloss-over crucial details (e.g. whether the imagery could be accurately georeferenced or whether it was suited to change detection). With any fine-scale mapping task that is to be applied over a large spatial extent, the 'devil is in the details' and these details can be the difference between whether the task is feasible or not. Therefore, it is worth investigating most of the references further. While the complete papers could not be provided due to copyright restrictions, direct URLs have been given in the reference list to make them easy to obtain.

Directly relevant reports and studies

In 2003, CSIRO prepared a scoping report to determine the feasibility of using remote sensing to assist in measuring/mapping 29 indicators defined in the Pilot SRA, largely from the original Physical Habitat theme (link to report). This report rated the feasibility of using remote sensing to measure/map each indicator and suggested which type(s) of remote sensing platform(s) would be required, along with a very brief comment about the processing required (CSIRO 2003, p.25-46). To achieve the largest number of the desired indicators, a suite of sensors were suggested as being required. The considerations and costs are discussed, along with sample imagery from the various sensors (CSIRO 2003, p.49-78). The recommended sensors are stated and elaborated on here briefly:

- Airborne hyper-spectral imagery (e.g. from Hymap or CASI) for better differentiation between riparian vegetation species (than multi-spectral imagery). This type of sensor was also suggested as being potentially capable of extracting information on macrophytes, river habitat types (i.e. riffles, pools), bed material (in clear water) and some water quality indicators. This has been supported by more recent literature (e.g. Marcus et al. 2003; Gilvear et al. 2004a), although these studies rely largely on visual processing/interpretation of the imagery (as opposed to automated processing/extraction).
- More extensive coverage using high to moderate spatial resolution (0.6-5m) satellite imagery (e.g. from Quickbird, IKONOS, SPOT5) for recognition/detection of required

features. The multi-spectral information from these sensors has coarser spatial resolution (2.4-10m respectively) but still offers some ability to differentiate between vegetation types (particularly when supplemented with hyper-spectral imagery). Multi-spectral information was not found to be as well suited for more subtle differences between species, habitats, etc. In terms of spatial resolution, Priestnall and Aplin (2006, p.2116) agree that it is over this range (1-10m) that a critical threshold is observed when attempting to accurately locate any linear features (e.g. river banks, roads, riparian vegetation zones), which are considered essential for many of the SRA indicators.

- Airborne LiDAR to produce high-resolution digital elevation/surface models (DEM/DSM) for determining channel, floodplain and vegetation characteristics. To differentiate riparian vegetation species and various landform characteristics, many of the feasibility findings from CSIRO rely upon using a combination of data sources. Airborne LiDAR provides the most valuable addition during processing, as its ability to penetrate through vegetation and give multiple returns can be paired with spectral characteristics to provide greater discriminatory power not possible with only passive sensors. However, the use of multiple data sources places much greater demand on positional accuracy, which increases pre-processing costs substantially.

Throughout the CSIRO report, there are many potential issues that could reduce the feasibility of a remote sensing solution. Many indicators are listed as being sensitive to in-stream shadows, high turbidity and overhanging vegetation, all of which are present to various degrees in Australian streams. Therefore, these details cannot be overlooked when evaluating remote sensing solutions. Recent work using airborne multi-spectral and LiDAR data in the South Para River, South Australia, has faced substantial difficulties with these issues when attempting to map in-stream pools, which is just one of the indicators desired within the SRA (S. Wealands, eWater CRC, pers. comm.). The CSIRO report recommends undertaking the remote sensing data capture during late spring/early summer and in the middle of the day when solar elevation is highest (i.e. to minimise shadows) and also when water levels are lowest (i.e. to reveal the maximum extent of the river channel). Other timing issues pertained to revealing particular differentiating trends in vegetation growth and for observing when turbidity is minimal (i.e. for maximum in-stream detail). The possibility of achieving these requests would differ between airborne and satellite-based sensors.

The report also comments on the need to atmospherically-correct and precisely georeference the imagery so that is can be reliably used for change detection, in-field validation and for combination with complementary datasets during analysis (CSIRO 2003, p.22). These issues can often be avoided in one-off, research-based studies as reported in the broader literature (e.g. Marcus et al. 2003, p.368), but for many of the feasibility findings presented by CSIRO these pre-processing tasks are necessary (and therefore must be accounted for in feasibility assessments). This demand could be reduced if change detection were not required and if all sensors were collected and co-registered from the one source (e.g. a specialised aircraft).

One of the key recommendations from the CSIRO report was to undertake a pilot study to help better estimate costs and feasibility of the proposed suite of sensors, as well as to develop new indicators that could be more amenable to a remote sensing solution. This pilot study was <u>not</u> undertaken at the time because there was no clear objective for using remote sensing in the SRA (F. Bouckaert, MDBC, pers. comm.). Since this time, the MDBC has also started working on a strategic paper regarding remote sensing, which recognises the need to combine resources with agencies from the states/territories for collection of remote sensing data. The draft strategic paper shows the beginnings of a proposed acquisition program that aims to leverage off state coordinated imagery programs.

Currently, the DSE have commissioned a pilot study (link to tender) to evaluate SPOT5 and Quickbird imagery for determining riparian and in-stream indicators in Victoria, consistent with the current ISC measures completed on the ground. This study aims to evaluate whether the riparian vegetation and physical form indicators can be comprehensively mapped using remote sensing (as opposed to the on-ground field work currently undertaken by Catchment Management Authorities (CMAs)). This study has completed the ground-truthing and should be complete by the start of 2008 (S. Marwood, DSE, pers. comm.). Dr Stuart Phinn (Centre for Remote Sensing and Spatial Information Science, University of Queensland) and his colleagues are undertaking this study, although no reports are as yet available through the DSE. This study should provide some clear evidence from Australian rivers as to the true feasibility of multi-spectral satellite-based remote sensing approaches.

There are two groups working with airborne remotely-sensed data for looking at river characteristics in Australia. Both groups are working with data provided through Airborne Research Australia (ARA), consisting of airborne LiDAR, multi-spectral (line scanner) imagery and digital aerial photography, although these are all research-grade products and the pre-processing, georeferencing and orthorectification is still in development. Researchers in the A1 project (titled “Theories of landscape ecology”) within the eWater CRC (at The University of Melbourne) have been undertaking analysis of this data for identifying connectivity of in-stream pools in the South Para River, South Australia. They are using a combination of multi-spectral image classification that is subsequently refined using LiDAR-derived terrain characteristics. This study has faced difficulties with co-registration of data sources, as well as problems due to in-stream shadows (from overhanging vegetation and non-optimal sampling time) and poor spectral differentiation between vegetation types (S. Wealands, eWater CRC, pers. comm.). This study is integrating data from multiple sensors during image processing and analysis. Researchers at the Australian Rivers Institute (at Griffith University) are also working with this same suite of sensors along with data from the ASTER satellite/sensor to map alluvial gully erosion in tropical rivers throughout Far-North Queensland. They are using ASTER data and object-based classification to define the regions of interest, while the airborne data is used for calibration/validation of their classification (Knight et al. 2007).

The other relevant work is being undertaken by Department of Water, Land, Biodiversity & Conservation (DWLBC) in South Australia. Glen Scholz and colleagues have been using oblique videography (from a helicopter flying along the stream) to map a range of stream features, relying on manual interpretation. Oblique videography is unlikely to yield positionally-accurate spatial datasets (although points can be approximated), but it does provide a documented coverage of a region and can be a substitute for field work. A brief overview of their methodology (link to document) outlines what they have found and their approximate costing.

Desirable indicators from remote sensing for the SRA themes

The report from CSIRO in 2003 evaluated 29 indicators from the Pilot SRA Physical Habitat and Water Processes Themes. Since then, the indicators required for these themes have been re-evaluated, although they are yet to be finalised. The draft strategic paper on remote sensing (by the MDBC) and recent discussions with SRA staff have led to a refined list of indicators that are considered of most relevance to the Physical Form and Riparian Vegetation/Floodplain themes in the SRA. The items in this list have then been grouped into those that would be interpreted from the remotely sensed sources (i.e. imagery and elevation models) and those that could be derived from the interpreted data. This list is only indicative of the needs of SRA and is not an 'official' list (as such a list is yet to be defined/provided).

Riparian vegetation theme

- Interpreted/classified from remotely-sensed sources
  - Riparian vegetation species
    - If possible, particular vegetation species would be mapped, although the mixed response within a pixel may preclude this in all but the highest resolution imagery and even then the spectral differences may be too subtle.
  - Riparian vegetation units
    - If individual species cannot be mapped, then some form of classification of vegetation units/groups would be suitable. These should focus on separations such as riverine/terrestrial, native/non-native or possibly different growth stages.
    - These units would be based on certain characteristics, such as similar vegetation structures or growing regimes. At the coarsest level, this would need to separate riverine/terrestrial vegetation.
    - Vegetation units could be aggregated together into meaningful groups for helping with designing stratified site selections and/or aggregation of field observations.
- Derived measures
  - Riparian vegetation characteristics
    - The riparian vegetation mapping must facilitate calculating variables including percentage vegetation cover, vegetation connectivity, riparian vegetation width, vegetation density, fragmentation, stream overhang, canopy complexity, vegetation health/vigour and some measure of the stage of vegetation regeneration.

Physical form theme

- Interpreted/classified from remotely-sensed sources
  - Definition of river banks/channel
    - These features must be delineated for use in measuring river planform and also for deriving some of the riparian vegetation characteristics.
  - Definition of floodplain extent/valley width
    - This should define where the floodplain extends to, which is required for determining a range of vegetation characteristics.
    - Currently this is being undertaken using a simple hydrodynamic model and the best-available DEM. Alternate, remotely-sensed methods would be desirable.
  - River reach depth/flow characteristics/stream habitat
    - This would involve identifying in-stream habitats (e.g. riffles) and stream depths (or some classification of depths), with a need for technology that captures information through the water column.
  - Features suggesting channel change
    - This is any evidence that reveals changes to river features, such as erosion or bank development, which can be used to define geomorphic trajectories. This may require analysis of multiple images to detect change.

- Derived measures

    - River planform measures
        - These are measures describing the shape/pattern of the river across the landscape and include, amongst others, sinuosity and meander wavelength.
        - These measures are often classified to provide groupings of rivers/channels with particular patterns.

Hydrology theme

- Interpreted/classified from remotely-sensed sources

    - Identification of the wetted network
        - This would determine where water currently exists within the broader river network, which would be valuable for sampling site selection (to help avoid visiting non-wetted sites).

- Derived measures

    - Waterbody type assessment
        - This would involve using the wetted network along other ancillary information to classify water as in-channel, floodplain, pools, etc.
        - These classifications could be used to determine indicators of hydrological connectivity.

Other useful indicators

- Interpreted/classified from remotely-sensed sources

    - Emergent aquatic macrophyte species
        - From mapping of in-stream vegetation (e.g. reeds), the area and relative abundance of macrophytes could be determined.
    - Lateral and longitudinal barriers
        - These are in-stream features that interrupt flow, such as levees, weirs, natural waterfalls, etc.
    - Sediment type
        - This is the differentiation of in-stream and emergent sediments, such as gravels and sands.
    - Large woody debris in and near rivers
        - The mapping of wood can be used for determining actual and potential levels of in-stream wood. This feeds into any type of ‘snag’ assessment also.
    - In-stream algae/periphyton/biofilm
        - Determining presence/absence of algal growth on bed sediments.

This list is indicative of the needs of SRA and should help the reader to appreciate the types of information that would like to be obtained from remotely sensed data sources. The scales at which these indicators occur varies from the valley-scale (e.g. floodplain extent) down to very-fine scale (e.g. sediment types, algae), as well as considering ‘underwater’ (e.g. bed type). The following section provides some information on the types of sensors that are available, after which the remainder of this document will review existing published literature that discusses the potential for these indicators to be interpreted from remotely sensed sources.

Background information on passive and active sensors

There are a number of textbooks, papers and web-based resources literature regarding remote sensing. All studies using remote sensing have to make critical choices between the sensors used, which each have a defined spatial resolution (i.e. the size of features that can be determined), spectral and radiometric resolution (i.e. the attributes that can be determined for features) and temporal resolution (i.e. the frequency with which the data is potentially available). Any choice of sensor involves some trade-off between these resolutions, with temporal resolution being the most frequently sacrificed factor in remote sensing (mainly due to the cost of imagery). The scoping report by CSIRO contains a useful overview of sensor technologies, capabilities and some estimates of cost (CSIRO 2003, p.88-99). For a more complete list of current and forthcoming remote sensing instruments, Metternicht et al. (2005, p.292, 295) provides some summary tables, while the imagery vendor Sovzond has a useful website (link to website) containing the vital statistics of satellite sensors.

From reading these resources, it is clear that passive and active sensors have different uses and are suited to different situations (e.g. active sensors have more ability to penetrate through atmospheric conditions, water and vegetation). One of the most useful active sensors for river-based studies is LiDAR, which comes in different forms and can provide both topographic and sometime bathymetric information (but bathymetry comes at the cost of spatial resolution). When active sensors are used in conjunction with passive sensors (e.g. multi- or hyper-spectral), the solution can provide a valuable resource for river and near-shore studies. A LiDAR workshop conducted by the United States Geological Survey (USGS) provides an excellent overview of these technologies and their issues (USGS 2004, p.9-23). The introductory section of Gilvear et al. (2004a, p.379-381) provides a nice overview of how LiDAR and hyperspectral imagery have been used within rivers. The recent article by Priestnall and Aplin (2006) gives a more general review of remote sensing requirements for rivers, while Ehlers et al. (2006, p.835-836) focus more on how airborne remote sensing has developed recently. Legleiter et al. (2004) provides a very detailed study of how well passive sensors could feasibly measure in-stream characteristics and the discussion/conclusions (p.506-508) are particularly useful.

The choice between airborne and satellite based remote sensing is generally influenced by the project needs (i.e. considering costs, coverage). Typically, airborne imagery is more expensive to collect, but it is also capable of capturing data with higher spatial resolution. There is also the possibility of using hyper-spectral scanners from aircraft, which is currently only available at coarse resolutions from satellite. The lower flying height of aircraft sensors allows some atmospheric effects that could hamper the ability to capture water-leaving radiance to be avoided (Legleiter et al. 2004, p.506). However, satellite-based sensors provide more routine imagery for monitoring, as they are always produced from the same perspective. Another positive for airborne remote sensing is the ability to run a suite of sensors from the one platform. This is in contrast to satellites that generally only provide one suitable sensor and thus require greater georeferencing efforts to make them usable with other data sources (such as LiDAR).

The Leica ADS40 instrument (link to website) is one example of a sensor capable of producing ultra-high resolution data that could be useful for river based studies (Ehlers et al. 2006, p.836). This sensor is currently being used by the Australian Defense Force for rapid, detailed mapping in the field (Sterling 2007). Trinder (2006) provides brief comments and an overview on these new digital airborne cameras. Yotsumata et al (2004) state that the ADS40 has been shown to have the potential for 1:2,500 scale mapping in Japan. Over a 3 months period in 2004, ADS40 imagery was acquired (link to article) for orthophoto production over approximately 380,000 square miles (approximately 1 million square km) of land in Texas, Idaho and Louisiana (comprising 10Tb of data) for the USDA Farm Service Agency (FSA).

One active remote sensing method that is not covered in these reviews is airborne electromagnetic (AEM) surveys, which are being used extensively in Australia for mining applications and also for salinity mapping. These sensors take a measurement that has a sampling footprint of >150m radius (depending on flying height), which is much coarser than is required by river applications (1-10m spatial resolution), yet they provide an interesting data source with very different capabilities to the other technologies mentioned here and can reveal other information of interest to catchment managers. Dent (2007) provides a discussion of this technology.

A spreadsheet summarising sensor characteristics, along with some relevant costs (obtained from the draft strategic paper on remote sensing for the MDBC) is included (link to spreadsheet). This includes a number of upcoming satellite sensors (e.g. GeoEye, Resurs

DK1) as well as details of some common airborne sensors (e.g. CASI, ADS40). The scoping report from CSIRO (2003, p.53) also provides estimates of cost. A more applied example of costing, particularly for a riverine study, is provided in Gilvear et al. (2004b, p.808-809). It is extremely difficult to provide a complete list of sensors due to the rapid development underway, although this spreadsheet provides a good resource for an overview of relevant technologies and how they compare to one another.

Evidence from literature regarding potential SRA indicators

There have been a number of studies looking at mapping in-stream features and other catchment characteristics from remote sensing platforms. Most of the published studies interpret remote sensed data using empirical relationships derived from ground observations collected simultaneously with the remotely sensed data (as used for supervised classifications). However, Legleiter et al. (2004) argue that consideration of physical principles of light interaction with the water column can provide more robust methods, particularly for mapping water depth and hydraulic habitats in shallow rivers. This has a similar theme to the brief discussion by CSIRO (2003, p.22) regarding field validation, where using field spectral measurements to build a 'spectral library' for common image features is mentioned. Both of these approaches take a more holistic view of the image processing task, rather than simply being focussed on interpreting features from the imagery for a single project. For evaluating remote sensing methods in larger-scale studies, these more rigorous methods of interpretation are likely to be needed.

The following discussion of the published literature provides links and comments on the literature relevant to the 'potential SRA indicators' identified earlier in this review.

Riparian vegetation

Mapping vegetation in the riparian zone has not been systematically accomplished across many watersheds/catchments, largely due to past approaches relying on aerial photography for sufficient spatial resolution (Goetz 2006, p.133). The spatial resolution of common multi-spectral satellite imagery (i.e. Landsat at 30m) has been only marginally sufficient for determining small-scale variability in the narrow riparian strips and is confounded by mixed pixels. By using higher-resolution satellite imagery and LiDAR, techniques for determining proportional estimates of vegetation within Landsat pixels can be obtained, as well as much more detailed mapping (albeit with different challenges). Goetz (2006, p.141) points out that while use of this finer-resolution data is technically feasible in research applications, it may not be practical for management applications in larger areas.

Multi-spectral images have long provided the means to mapping vegetation, although hyper-spectral imagery can permit greater differentiation. Similarly, when temporal coverage is available, the different growing patterns of vegetation can be used to identify species using the time series. Most commonly, the Normalized Difference Vegetation Index (NDVI) is calculated (using radiance in the near-infrared and red bands) and together with the visible bands (R, G, B) forms the basis of most vegetation classifications.

For very-high resolution data, Ehlers et al. (2006) have used data from airborne sensors (similar to the ADS40) to simultaneously capture imagery and elevation models. They analysed data collected in 1999, 2000 and 2002. To help understand how this technology might be applied over larger areas, their research focuses on automated techniques for mapping. They use a multi-stage classification/analysis method for mapping 'biotopes' (i.e. groupings that consider more than just vegetation type, such as height or distance from water). For example, areas were firstly separated into vegetation/non-vegetation, then separated into high/low vegetation (using elevation data) prior to subsequent unsupervised classification within each area (to identify species differentiations). To deal with problems of shadowing, they used GIS analysis (e.g. neighbourhood rules) to assign pixels to nearby categories. The 12-bit radiometric resolution of the data helped to differentiate pixels within shadows as they still contained variability (which would have been limited in 8-bit imagery). Sensors with higher radiometric resolution (such as the 12-bit imagery produced by CASI) were also found to be valuable for dealing with shadows in Leckie et al. (2005, p.152). They found in-stream features could be still recognised within shaded areas and classified accordingly, making radiometric resolution a significant consideration. Legleiter et al. (2004, p.503) also support this, stating that 8-bit systems are limited in their ability to map subtle channel features, particularly in deeper water.

Goetz (2006, p.138) also refers to an alternate type of LiDAR that uses a broad-beam (and captures the full-spectrum) for obtaining an integrated measure of vegetation. The Laser Vegetation Imaging Sensor (LVIS) (link to website) is a NASA research instrument that produces imagery with a spatial resolution of 10-25m and can be used for recognizing particular vegetation characteristics such as the vertical structure of tree canopies and providing estimates of biomass. Goetz (2006) also points out that LiDAR instruments are not a panacea for mapping riparian zones, but they do provide information on the vertical structure of vegetation that can augment the more traditional passive sensors used. For example, vegetation height, cover and attributes of canopy structure have been mapped using single-pulse and full waveform airborne LiDAR (Lefsky et al. 2002).

Floodplain and physical form

The floodplain is one aspect of mapping/monitoring stream condition that is very difficult to assess in the field, as it can be a very large area that is difficult to accurately define. Therefore, remote sensing or alternate analysis methods that can provide floodplain indicators are considered very valuable, whereas many of the other potential indicators could be assessed in-situ. Hydrodynamic modelling studies that ‘virtually inundate’ a digital elevation model are most commonly used for defining floodplain extents, although this depends on accurate representation of the surface (which is often lacking) and surface roughness amongst other things. LiDAR-based DEMs, which can represent the bare-surface, are most suited for this, although consideration about the spatial resolution required must be made. For measuring water surfaces (e.g. flood inundation extents), RADAR imagery has been used (e.g. Horritt et al. 2001) and new high-resolution RADARs such as TerraSar-X will improve the spatial resolution/accuracy for such tasks.

For in-stream studies concerned with bed shape and water-depth/bathymetry, LiDAR instruments operating in the blue-green part of the spectrum are used (USGS 2004). This is in contrast to most published studies which use terrestrial LiDARs that operate in infrared wavelengths and do not penetrate far into the water column. Bathymetric LiDAR provides some options here, with NASA having developed the EAARL instrument, which is a compromise between the terrestrial and full bathymetric LiDAR that are commercially operated (USGS 2004; Kinzel et al. 2007). EAARL uses a weaker laser pulse than full bathymetric LiDAR, but this provides greater spatial resolution (due to a higher frequency) and still penetrates shallow water. Kinzel et al. (2007) gives an overview of this instrument and looks at the difficulties of resolving both terrestrial and bathymetric heights accurately.

Multi- and hyper-spectral sensors have been used from airborne platforms for studying rivers in the UK and USA. Bryant and Gilvear (1999) provide a detailed look at change detection from airborne sensors (using Daedalus ATM), particularly for evaluating geomorphic change and changing riparian vegetation. They stress the challenge in pre-processing the data so that change is detectable. They claimed to detect changes in the order of 10cm in depth (Bryant and Gilvear 1999, p.314), using a regression-based approach to relate the airborne multi-spectral data (from the near-infrared bands) to ground measurements of water depth (r^2 = 0.67) (Winterbottom and Gilvear 1997).

Leckie et al. (2005) used 8 hyper-spectral bands to differentiate in-stream features from 80cm CASI imagery (i.e. an airborne hyper-spectral sensor that can be reconfigured to observe in different bands). Their classification was able to differentiate features within the shadows (due to CASI recording 12-bit data), which were then recombined. Again, it must be noted that this was in a mountain stream in Canada and thus an optimal situation. Gilvear et al. (2004b) use airborne multi-spectral imagery and digitized colour aerial photographs to map exposed gravel, deep water and shallow water in addition to a number of terrestrial features. With the exception of the shallow water class, multi-spectral images provided greater accuracy (62% for shallow water, 83% for deep water and 94% for exposed gravel). Sun glint on water surfaces and shadows caused by high banks, trees and buildings were identified as the main cause of inaccuracies.

Wright et al. (2000) use multi-spectral images to map morphologic units (eddy drop zones, glides, low gradient riffles, high gradient riffles, lateral scour pools, attached bars, detached bars, and large woody debris). Marcus et al. (2003, p.378) used a similar approach and obtained classification accuracy of 69% in third-order streams, increasing to 86% in fifth-order. The mapping accuracy improved in larger rivers because the various hydraulic zones were more homogeneous and therefore fewer pixels were contained in the transition zones (where most misclassification occurs). Hydraulic habitat types have also been mapped using hyper-spectral image data with shortwave-infrared wavelengths proving most useful in distinguishing habitat types (Legleiter 2003). In a number of studies, the subjective nature of on-ground mapping has made it difficult to access classifications perfectly. Marcus et al. (2003, p.378) point out that the reflectance from in-stream habitats represent variations in surface turbulence, turbidity, depth, algae and substrate size/colour/composition, not to mention any atmospheric effects (e.g. hazy conditions). It is also worth noting that these studies have largely been conducted in optimal stream conditions (e.g. clear, shallow, gravel-bedded streams in the USA). Some of the work from Gilvear et al. (2004a) has been in more challenging, turbid environments such as estuaries. Overall, the discussion provided in Gilvear et al. (2004a, p.384-391) raises most of the key issues regarding these indicators and poses some important questions for evaluating these approaches.

Hydrology

Many of the same issues outlined above concerning in-stream habitats and the floodplain are relevant to mapping the existing water in streams. However, the surface-water boundary along rivers has been mapped using airborne multi-spectral imagery based on a near-infrared band and the NDVI index (Whited et al. 2002; Lorang et al. 2005). The near infrared band is suited to this purpose because the reflectance of water surfaces at these wavelengths is generally lower than for the surrounding ground (and is largely absorbed by clear water). If the spatial resolution is adequate and there is no interference from overhanging vegetation and shadows, then the near-infrared band on most multi-spectral sensors could be sufficient to achieve this, although turbidity will cause some problems.

There do not seem to be any studies using airborne SAR to map in-channel features, possibly due to the relatively coarse resolution of SAR imagery in the past. The use of high-resolution SAR imagery may offer some promise here, with data from the new TerraSAR-X sensor being suited to mapping flooded areas (based on the sample imagery available). If so, then data extraction methods such as the ‘snake algorithm’ of Horritt et al. (2001) may be useful to identify the water edge from the SAR imagery.

Other indicators

The analysis of airborne digital imagery has built on experience in aerial photogrammetry to map the channel topography above and below the water surface (Westaway et al. 2003). Airborne digital imagery has also been used to map sediment grain sizes along dry river beds (Carbonneau et al. 2005; Verdu et al. 2005) and in shallow clear water where the river bed is visible. This work used helicopter-based imagery with a spatial resolution of 3cm. However, the ground resolution of the image gives the lower size threshold below which grain sizes are undetectable (Carbonneau 2005). Water depth has also been mapped in clear water based on an analysis of optical image brightness (Fonstad and Marcus 2005).

Many of the other indicators in the potential SRA list have also been mentioned in the previous sections. If not mentioned, they were not encountered in initial literature searching regarding remote sensing application in rivers.

Image processing and analysis

CSIRO (2003) refer to a number of different pre-processing and image processing tasks in their scoping study of SRI indicators. For pre-processing, there is a need to convert the digital numbers recorded by sensors into reflectance units, so that they can be compared over time (e.g. atmospheric correction, etc), which requires field samples from different targets (CSIRO 2003, p.22-23). When absolute accuracy is important (e.g. when combining sensors or undertaking change detection), geometric corrections will be required (Bryant and Gilvear 1999, p.311). Once pre-processing has been undertaken, CSIRO (2003, p.25-46) identify a number of general processing tasks that would be used, including classification (presumably supervised using the field samples referred to), DEM analysis (for terrain features), GIS analysis (i.e. combining multiple data sources or processing derived features) and change detection (from multiple images). No specifics are provided, nor is there an indication of whether these processing tasks could be automated for the various indicators (which would determine their feasibility when covering a large area).

Ehlers et al. (2006) used automated methods for analysing multi-spectral data from airborne sensors. This work involved a decision tree classification, in which various initial steps (e.g. separating vegetation/non-vegetation, splitting these categories by vegetation height) were used to improve the performance of the unsupervised classification. They still relied upon visual checking and manual correction to the automatically-classified results (Ehlers et al. 2006, p.841).

Gilvear et al. (2004b, p.808-810) cite many past studies in stating that "more than four bands does not appear to improve accuracy assessment significantly [for channel hydromorphology]". However, this does not suggest hyper-spectral imagery is not valuable for identifying additional variables (such as more detailed vegetation categories) that cannot be differentiated using multi-spectral data. Gilvear et al. (2004b, p.810) also addresses the issues of whether visual assessment is required. They find that visual assessments are most reliable (but impractical), while automated methods have produced quite good classification accuracy. They encourage the use of more sophisticated classification procedures that employ additional topographic information and information on shape/texture.

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Appendix 2: Remote sensing options for physical form of rivers

Grouping and attributes	**Interested in change?**	**Priority for SRA**	**Relevant sensor(s)/data; likely processing required; other comments and examples of feasibility**	**Currently feasible**
Channel sinuosity Meander wavelength	Y	High	Calculate these measures using spatial analysis of existing topographic mapping datasets If existing data not suitable, use high-resolution imagery to create new spatial data representing stream banks, probably requiring visual interpretation but possibly with a semi-automated approach	Y (improved with new data)
Geomorphic stream type*	Y	?	Classification using either imagery or LIDAR data (or other elevation source) Probably reliant on visual interpretation, but automated methods might help remove some of the subjectivity in classification Classifications using fuzzy boundaries (e.g. probability of being in a particular type) would help to capture some of the ambiguity	Y (needs manual interpretation)
Paleochannels*	?	?	Electromagnetics or soil moisture hot spots could indicate these, but would require ground calibration data and the spatial resolution may not be adequate These may be manually detectable in high-resolution images, particularly if they contain water They may also be possible to derive using a hydrological model based on a LIDAR terrain model The ecological outcomes work on the Murray has looked at this	Y/N (dependent on needs for spatial resolution)
Channel bankfull width/depth (mean and variability)	Y	High	LIDAR could permit width to be done in areas where there is not a dense canopy or reed bed, largely based on manual interpretation (with some semi-automated assistance) Imagery is not useful here Depth may be determined if LIDAR is collected during low flows, but otherwise would require on-ground survey (as bathymetric LIDAR does not perform consistently in turbid environments)	Y (width) N (depth)
Channel gradient	Y	High	Existing DEMs or a newly captured LIDAR DTM could be used to determine this	Y

Grouping and attributes	Interested in change?	Priority for SRA	Relevant sensor(s)/data; likely processing required; other comments and examples of feasibility	Currently feasible
			Comment was made that low gradient streams have low power and, as a result, low resolution DEMs will not falsely predict high stream power	
Bankfull hydraulics*	?	?	LIDAR could provide this assuming no dense canopy at the bank top High resolution photogrammetry could provide this where the canopy is sparse (i.e. the derived digital surface model could actually see the ground surface as opposed to the canopy) Videography was considered to be too subjective	Y
Bank angle	Y	High	LIDAR could provide this assuming no dense canopy at the bank top	?
Bank sediment cohesivity	Y	Low	No options identified	?
Bank and floodplain soil type*	?	?	Airborne and in-stream electromagnetics could be suited for this if spatial resolution is suitable, but would require calibration for each mission MDBC and DWLBC (SA) have undertaken this kind of work	N (difficulty with calibration and interpretation)
Bed material size	Y	Low	Hyper-spectral imagery gives greater capability to map this, but the improvements over other approaches is probably lost when working across whole basin (due to difficulties with variability) Hyper-spectral analysis is also confounded by water depth and turbidity Use of high-resolution imagery of exposed sediments shows promise, as undertaken by James Grove in Tasmania and also in broader literature	Y/N (depending on the stream characteristics)
Density of large, woody debris (LWD)	Y	Low	High-resolution imagery may allow woody-debris to be manually identified, but automated methods are currently unlikely	N
Active floodplain width	Y	High	A high resolution DEM of the floodplain generated using LIDAR or high-resolution photogrammetry could support hydraulic modeling, from which active floodplain width would be derived	Y
Structures on the	Y	High	Using a combination of LIDAR with imagery of inundation, any anomalies would reveal blockages	Y

Grouping and attributes	Interested in change?	Priority for SRA	Relevant sensor(s)/data; likely processing required; other comments and examples of feasibility	Currently feasible
floodplain (e.g. levees, banks, roads, bridges)			Manual inspection of high-resolution imagery would permit recognition of features, provided that features are not smaller than the ground sample distance of the imagery	(with manual inspection)
In-stream geomorphic units and physical habitats*	?	?	Multi-spectral high resolution imagery can be classified with various levels of success (as evidenced by recent research efforts) Stream shading, inundation, canopy cover and turbidity all impact on feasibility	Y
Permanency of wetlands*	Y	?	Any imagery with sufficiently high spatial resolution to visually detect these would permit mapping, while change would just require imagery that can be consistently recaptured Depending on size of wetlands being considered, existing satellite imagery may be suitable and provide greater temporal coverage than possible with airborne sensors Associations and anomalies between topography, temperature and vegetation would indicate groundwater/surface water interactions DEW have been undertaking this for significant wetlands (e.g. RAMSAR)	Y
Vegetation dependency on groundwater*	Y	?	The change in vegetation vigour in response to flood events will reveal this, so any multi-spectral imagery that can indicate vegetation vigour would be suitable (e.g. Landsat)	Y
Groundwater depth*	?	?	Airborne electromagnetics could provide an approximate measure of this and the spatial resolution needs should not be too high (as it is a spatially averaged measure)	Y
Erosion indicator*	?	?	No options identified	?

* metrics suggested during the project's workshop

Appendix 3: Remote sensing options for riverine vegetation

Grouping and attributes	Interested in change?	Priority for SRA	Relevant sensor(s)/data; likely processing required; other comments and examples of feasibility	Currently feasible
Vegetation extent (at the catchment scale) Area covered by vegetation groups	Y	High	Existing state and federal programs (which are Landsat-based) for vegetation mapping are valuable here, provided that there is temporal consistency to the mapping Classification of Landsat bands and ancillary data can provide particular vegetation classes of interest (although these could not be articulated by SRA representatives at the workshop)	Y
Vegetation extent (at the riparian zone scale) Derived measures of spatial arrangement and density of vegetation	Y	High	The existing mapping is not of sufficiently high spatial resolution for delineating the riparian zone, largely due to dependence on Landsat for differentiating vegetation This requires higher resolution (<10m) multi-spectral information (e.g. SPOT, ALOS), of which only the NIR band is available from satellites (highest resolution available is 2.4m from QuickBird) Airborne sensors are needed for high-resolution imagery with more bands, but swath width and extent of coverage is reduced accordingly This mapping could be automated once processing practices are agreed upon for different environments within the MDB, which can be based on a large existing body of research and evidence (e.g. TREEDEN data in Victoria) SRA may be able to influence broader land use/cover mapping programs to pursue higher resolution extent mapping using 4 bands (versus 7 from Landsat) – indicators of vegetation vigour could flow from this	Y
Broad classification of vegetation (e.g. equivalent to EVC)	Y	High	Feasible at catchment scale, but riparian zone scale will be limited by spectral resolution of imagery available (e.g. obtaining enough spatial resolution to go with spectral detail) Capabilities of differentiating basic vegetation groupings from 4 bands is necessary before moving forward, unless more bands can be captured consistently from airborne platform	Y/N (depending on grouping needs)
Taxon richness Composition	Y	Low	Would require visual interpretation of high-resolution imagery by experts, as automated classification is not considered reliable enough over large areas There is potential for hyper-spectral data to be used for mapping individual species in smaller areas, but this	N

Grouping and attributes	Interested in change?	Priority for SRA	Relevant sensor(s)/data; likely processing required; other comments and examples of feasibility	Currently feasible
Nativeness			requires development of spectral library for species being recognised (which is a challenging task when considering diversity across the MDB) Point was made that while hyper-spectral solution is technically feasible, the current working ground for large projects is multi-spectral, so any assessment of feasibility should consider what can be done with this level of spectral detail	
Physiological status Surrogate for tree canopy vigour Common vegetation indicators	Y	High	Workshop was confident in using well-established methods (NDVI, FPAR, LAI) for change detection, but stressed need for temporal consistency of imagery and greater spatial resolution than currently used Change detection would require benchmarking and ground sampling to confidently estimate change in vigour and vegetation types Combined with vegetation extent mapping, this provide the basic ‘census type’ information required by the SRA and is based on existing, standard approaches that workshop participants were confident in	Y
Vegetation structure Number/height of strata Height of canopy for each strata Height of canopy	Y	Medium	These characteristics require LIDAR, as they must penetrate the canopy and give multiple returns The basic ‘height of canopy’ measure could be determined using a surface model (from photogrammetry techniques), but far greater information on the vertical structure of the canopy would come from LIDAR	?
Presence of recruits Age/size/class structure	Y	Low	No options identified	N
Provision of habitat Standing dead trees Standing grasses	Y	Low	Visual interpretation of change in NDVI combined with visual imagery (to avoid confounding effects from automatic classification, such as when a tree dies and the grasses below it grow, thus giving higher NDVI) Requires very high-resolution imagery	N
Stream shading, extent of overhang	Y	High	Could derive stream shading and overhang by combining high-resolution vegetation extent mapping with ‘blue line’ watercourse datasets (although these represent centerline of stream, not both banks)	Y (particularly with improved stream

Grouping and attributes	Interested in change?	Priority for SRA	Relevant sensor(s)/data; likely processing required; other comments and examples of feasibility	Currently feasible
			Improved bank mapping from visual interpretation (or semi-automated feature extraction) would improve these measures substantially and also have value for physical habitat theme Some efforts underway at Geoscience Australia to improve blue line mapping – SRA may be able to influence this work to better service their needs	bank mapping)
Soil moisture, EC*	?	?	Use of L-band RADAR, thermal imagery or electromagnetics, although all of these approaches mayb e limited in spatial resolution (depending on needs)	N
Water quality Salinity, temperature, turbidity, chlorophyll*	?	?	Hyper-spectral and thermal imagery with spectral signatures and ground truthing make this technically feasible, but difficult to reliably apply over a large area in automated manner	?

* metrics suggested during the project's workshop

Appendix 4: Satellite and airborne sensor list

This table has been expanded and adapted from the ‘Draft strategic paper on remote sensing’ that was written by the MDBC Natural Resources Information Program. All cost estimates have been reproduced from that paper and the sources of information vary. This table should only be used as a means of comparing available platforms/sensors and further details should be sought about any sensors of major interest (and their cost).

Sensor	Spectral resolution	Spatial resolution	Swath	Temporal resolution	Cost	Additional details
Aerial Photography: Images collected by airborne camera. This useability of these images is generally limited by errors associated by the angle the image was taken at, registration and the processing involved in merging the individual images.						
Analogue photography	Panchromatic Colour Colour infrared	Various	Variable	User and weather dependant	**2006 costs:** $90 per frame to fly and buy hardcopy. Scanning and georeferencing are additional costs.	
Multispectral (Aerial): Images collected in more than one spectral band or wavelength interval by an airborne sensor.						
Spectra DMSV, Daedalus-1268, ADAR	3-20 bands	0.5 – 10m	Variable	User and weather dependant	**2006 costs:** approx $2-6 p/km2 for georeferenced image	
ADS40	Pan, Visible and NIR (12bit), Stereo Vision	25cm from 2500m,	Variable with height, approximately 1:1	User and weather dependent		NSW Lands operates ADS40 from their aircraft based in Bathurst

Sensor	Spectral resolution	Spatial resolution	Swath	Temporal resolution	Cost	Additional details
Multispectral (Satellite): Images collected in more than one spectral band or wavelength interval by a satellite sensor.						
SPOT 5	3 VNIR 1 SWIR 1 Panchromatic	2.5m Panchromatic 10m VNIR	60km			
ALOS: PRISM – Panchromatic RS instrument		2.5m	35km	46 day recurrent period		25K scale DEM generation
ALOS: AVNIR-2 – Advanced Visible and NIR Radiometer		10m	70km			Land use classification
Ikonos	3 Visible (blue, green, red) 1 Near infrared 1 Panchromatic	1m Panchromatic 4m Multispectral	11.3km x 11.3km	3-4 day recurrent period	**Agrecon (now):** Archive data: $18 p/km2. New tasking: $35 p/km2. **2003 costs:** Archive data: $12 km2 for 4mMS; $37 km2 for 1mPAN and 4mMS. New tasking: $290 km for 1mPAN and 2.4mMS.	Users purchase data within a user-defined boundary even if it is irregular in shape. Can produce a 1m DEM. Archive data is available from 1999.
Quickbird	3 Visible (blue, green, red)	0.6m Panchromatic	16.5km x 16.5km	3-7 day recurrent period.	**Agrecon (now):** Archive data: $36 p/km2. New tasking: $47 p/km2. **2003**	Users purchase data within a user-defined boundary even if

Sensor	Spectral resolution	Spatial resolution	Swath	Temporal resolution	Cost	Additional details
	1 Near infrared	2.4m Multispectral			**costs:** Archive data: \$43 km2 for 2.4mMS; \$51 km2 for 0.6mPAN and 2.4mMS. New tasking: \$290 km2 for 0.6mPAN and 2.4mMS.	it is irregular in shape.
GeoEye (formerly OrbView5)	4 VNIR 1 Panchromatic	1.65m 0.41m	15.2km	1-3 days		Due for launch early 2008
RapidEye (upcoming)	3 Visible, 1 Pan 1 red-edge, 1 NIR	6.5m	158km	1 day		Due for launch Nov 2007
TopSat	Pan and Visible	2.5m Pan, 5m Visible	17km x 17km			Recently operational
Resurs DK-1	1 Panchromatic 3 MS (G, R, NIR)	1m Panchromatic 3m Multispectral	28.3km			Being marketed by Sovzond in Russia
WorldView-2	1 Pan, 8 MS	0.5m Pan, 2m MS	16.4km			Due for launch in 2009
Hyperspectral (Aerial): Images collected in multiple narrow spectral bands over a contiguous spectral range by an aerial sensor.						
CASI or Hymap	20 bands	0.5m – 10m	100km2	User	**2006 costs:** >\$20 p/km2 for georeferenced	

Sensor	Spectral resolution	Spatial resolution	Swath	Temporal resolution	Cost	Additional details
Hyperspectral (Satellite): Images collected in multiple narrow spectral bands over a contiguous spectral range by an aerial sensor.						
MERIS	15 bands	300m	2500km wide			
MODIS	36 bands	250m – 100m	2048km wide			
Hyperion	200 bands	30m	7.5km x 100km			
Lasers (Aerial): Point clouds collected and often processed into digital surface and terrain models (DSM/DTM)						
LiDAR (terrestrial)		0.15 – 0.4m horizontal	0.8 – 2.184km			Natural surface terrain, buildings, vegetation, contours and 3D models
RADAR (Satellite): 24 hour coverage (not weather dependent), high precision monitoring for change (mm), high accuracy DEMs (2-4m depending on elevation)						
TerraSar-X	X-Band RADAR	1m - 16m	5km - 100km	2-11 days		Cloud-free and day-night land observation
ALOS: PALSAR – Phased Array Synthetic Aperture Radar		20m	70km			Cloud-free and day-night land observation

Appendix 5: List of workshop participants

Name	Organisation
Barbara Downes	Melbourne University
Chris Gippel	Consultant
David Gilvear	University of Stirling, UK
David Williams	University of Canberra
Frederick Bouckaert	SRA, MDBC
Ian Overton	CSIRO Water for a Healthy Country
James Grove	Monash University
Jeff Walker	Melbourne University
Jorg Hacker	The University of Adelaide
Kasper Johansen	University of Queensland
Kris Kleeman	NRI. MDBC
Lex Cogle	TLM, MDBC
Lucy Randal	BRS
Matthew Bethune	MDBC
Michael Reid	University of Canberra
Michael Wilson	SRA, MDBC
Mike Stewardson	Melbourne University
Mohammad Abuzar	DPI - Victoria
Neil Sims	ENSIS
Paul Wilson	DSE
Phil Tickle	Geoscience Australia
Sarah Spackman	DEWR
Simon Jones	RMIT
Stephen Wealands	Melbourne University