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Improving river flood modelling using high-resolution satellite and airborne observations: A case study in the Lower Barwon-Darling River

J. Hou, A.I.J.M. van Dijk and L.J. Renzullo

[a] *Fenner School of Environment and Society, The Australian National University, Canberra*
Email: jiawei.hou@anu.edu.au

Abstract: Floodwaters are critical for the survival of riparian wetland ecosystems. However, the complexity of river connectivity, morphology, and ecohydrology during flood events can lead to large uncertainties in river modelling, which limits our ability to predict what environmental flows are necessary to maintain ecological targets. This study aimed to reduce river modelling uncertainty during flood events by better constraining the river reach water budget during flood events. We examined if satellite- and model-based estimates of water balance term estimates could be combined with gauged river flow measurements to reconstruct the river water balance. Water volumes stored in the river reach were estimated by combining high-resolution satellite observations of water extent with a detailed digital elevation model (DEM). Simulations by the Australian Water Resources Assessment Landscape model (AWRA-L v6) were used to also estimate wetting losses (i.e., the amount of river flows used to replenish accumulated soil and groundwater deficits), open water evaporation and local runoff generation. To test the approach, we analysed a flood event between 20/12/2010 - 25/03/2011 in the river reach of the lower Barwon-Darling River in the northern part of the Murray-Darling Basin. The budget results suggested that local runoff, open water evaporation, and wetting losses were 5.33 GL, -21.18 GL, and -8.71 GL, respectively, with a remaining unresolved water balance term of was -9.15 GL. The negative balance was mainly due to uncertainties from river gauging data, surface water diversion estimates, and ungauged tributary inflow and distributary outflow. Although we were unable to remove these uncertainties fully, our analysis demonstrated that it is possible to use satellite observations to better constrain the river reach balance during flood events.

Keywords: *River modelling, river reach, water budget, flood, remote sensing*

1. INTRODUCTION

Floods play a crucial role in maintaining the health and vitality of river ecosystems. When floods occur, they can replenish soil and groundwater, enrich soil fertility, build floodplains, and revitalize wetlands, all of which are essential for fostering wildlife habitats (Talbot et al., 2018). The biota that inhabit river-floodplain ecosystems have the ability to adapt to changing flood levels, which creates a dynamic and diverse environment (Petsch et al., 2022). To properly manage these ecosystems, it's important to identify and quantify overbank flow onto the floodplain, the distribution of water on the floodplain and return flows to the channel. Doing so helps us understand the environmental water requirements needed to achieve ecological and environmental targets, especially in the Murray-Darling Basin in Australia (Swirepik et al., 2016).

Despite their importance, water dynamics during floods remain complex and poorly understood. One significant challenge is the insufficient network of river gauges that can provide spatially consistent measurements needed to understand river ecohydrology. Additionally, gauge stations often have large uncertainties in measuring extreme flows and cannot provide detailed flood extent and spatial depth information. Finally, detailed observations of complex surface topography and floodplain hydrodynamics are lacking, further contributing to significant knowledge gaps. These knowledge gaps pose significant challenges to accurately predicting environmental water requirements and accounting for water resources in river models, leading to large uncertainties in these predictions. Therefore, there is a pressing need to advance the knowledge base to understand the complex processes that occur during floods.

Kirby et al. (2008) and Van Dijk et al. (2008) developed water budgets for 145 river reaches across the Murray-Darling Basin. These budgets have proven to be a practical way of identifying uncertainties in river modeling and assessing our understanding of the water cycle, from individual reaches to basin-wide scales. One key finding of the water budget analysis is that only around 6% of the rainfall in the basin is transformed into available surface water resources, and approximately 42% of this surface water is used for irrigation (Leblanc et al., 2012). This underscores the limited availability of surface water resources for the environment, and highlights the critical importance of assessing environmental flow requirements in the region. The current water budget method has yet to identify "unspecified losses," which may be attributed to the replenishment of floodplains and wetlands and their associated evaporative losses (Van Dijk et al., 2008). As a result, quantifying water gains and losses on the floodplains and wetlands could significantly reduce uncertainties in water budget analyses in the Murray-Darling Basin. It is therefore essential to develop more accurate methods for assessing these water balance items to better understand and manage the water resources in the region.

The use of spatial satellite and airborne data can greatly reduce uncertainty in river models during floods by providing independent estimates of the different components of the river reach water balance. One such valuable data is the Digital Earth Australia (DEA) Water Observations product, which offers a detailed historical record of surface water dynamics using 30-m and 16-day Landsat images from 1986 to present (Mueller et al., 2016). However, despite the usefulness of the DEA Water Observations product, the relationship between extent and volume on the floodplain remains unclear. Fortunately, recent efforts in collecting and interpreting airborne stereophotography and laser scanning data across NSW have shed light on this important relationship. By combining elevation data with water presence data, it is now possible to determine spatial changes in the volume of water on the floodplain, a crucial development that can significantly improve our ability to close and predict the river water balance during floods.

This study aims to investigate an innovative approach to using river reach water budgets to improve river modelling, with a focus on flood events. We use the Australian Water Resources Assessment Landscape model version 6 (AWRA-L v6) (Frost et al., 2018a) as an example to estimate river balance terms such as floodplain wetting losses, local runoff and open water evaporation rates. Although the AWRA-L provides daily and 5 km landscape water balance simulations, including evapotranspiration, runoff, soil moisture, and deep drainage, it does not consider flood inundation in the modelling framework. To improve this framework, we include several unaccounted hydrological components, such as:

1) floodplain water storage changes using high-resolution satellite and airborne LiDAR observations
2) wetting losses (i.e., the amount of flood water used to replenish accumulated soil and groundwater deficits)
3) open evaporation from the inundation area
4) direct runoff from rainfall on the inundated area.

We subsequently investigate whether these data can be combined with other hydrometric measurements and estimates to reconstruct the river water balance.

2. METHODOLOGY

For this study, we chose to analyse a section of the Barwon-Darling River in the northern Murray-Darling Basin, located near the town of Bourke, NSW (Fig. 1). This river reach was chosen because it shows complex connectivity and a poorly constrained water budget during flood events. It is a semi-arid lowland river with an annual average rainfall of 330 mm and an annual stream flow of 3,500 GL at Bourke. The reach has a highly variable flow regime, extensive floodplains and wetland systems, and a meandering channel network. Surface water diversion is the main source of irrigation, primarily for cotton. The Geofabric delineates seven levee dams and two reservoir dams in this section (Fig. 1).

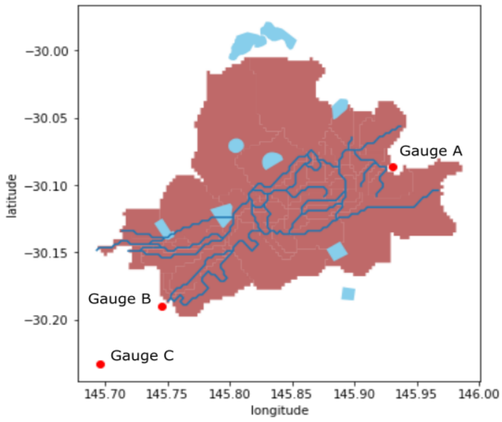

Figure 1. The study reach for the river reach water budget analysis (red dots: river gauging stations (Gauge A: DARLING@BOURKE TOWN (425003); Gauge B: DARLING@MYANDETTA (425038); Gauge C: DARLING@D/S WEIR 19A (425037)); dark blue line: river-floodplain channel; light blue polygon: leeve and reservoir dams; brown polygon: the study reach)

For the water budget analysis, we collected river flow data from three gauging stations managed by the NSW government (https://realtimedata.waternsw.com.au/). To reduce the uncertainties of river flow measurement, particularly during flood events, we averaged data from two downstream gauging stations (Gauge B and C, Fig. 1). While data from the upstream gauging station (Gauge A) is available from 1987 to the present, at least one of the two downstream stations provides flow measurements after 2002. Therefore, we calculated the water budget for this test reach only for the period 2002–present. Our analysis focused on a medium flood event during the period of 07/2010 – 07/2011, as satellite observations most thoroughly captured the development, peak, and retreat of this event.

We defined the study reach control volume as the surface water in the river channel and connected floodplain and wetlands between upstream and downstream gauging stations (Gauge A and B). The horizontal boundary of the reach was defined as the outer bound of all merged sub-catchments corresponding to the river network represented in Geofabric (Fig. 1). Exchanges with the soil, groundwater, atmosphere, or artificial storages all represent gains or losses from the control volume (Fig. 2).

To estimate floodplain water volume change ($\Delta S_{floodplain}$), we used an automated approach developed by Hou et al. (2022) in this study. We used a 1-m resolution LiDAR DEM product from the Elevation Information System (ELVIS) archive and 25-m and 16-day resolution historical Landsat-derived surface water observations (i.e., Digital Earth Australia (DEA) Water Observations product) from Geoscience Australia in this approach. The process involves (1) downscaling 30-m Landsat imagery to 5-m mapping by LiDAR DEM; (2) filling in missing data (e.g., cloud) in Landsat imagery for flood detection; (3) producing 5-m floodplain water depth mapping considering hydraulic connectivity; and (4) estimating 16-day floodplain water volumes from 1987-present based on Landsat and LiDAR. In addition, we estimated the inundation area changes in the river, floodplain, levees, and dams, which can be used to estimate other budget items below.

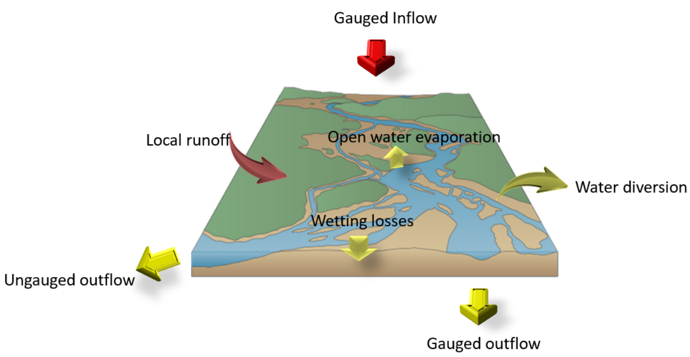

Figure 2. The concept of river reach water budget analysis (water gains: gauged inflow and local runoff; water losses: open water evaporation, water diversion, wetting losses, gauged outflow and ungauged outflow)

At the bottom boundary of the control volume, there are wetting losses from floodwater that replenish accumulated soil deficits. We used modelled upper (0 - 0.1 m) and lower (0.1 - 1 m) soil moisture estimates from AWRA-L v6 to estimate soil deficit dynamics. The average maximum storage in the upper and lower soil layer in the study reach is 32.81 mm and 197.85 mm, respectively. Wetting losses during a flood event were calculated as follows:

$$\Delta S_{wetting\_losses} = \frac{(S_{\max\_s0} - S_{s0(i)}) + (S_{\max\_ss} - S_{ss(i)})}{1000} \times A_{\max\_floodplain} \quad (1)$$

where $\Delta S_{wetting\_losses}$ is wetting losses (GL) for day i, S_{max_s0} and S_{max_ss} maximum storage (mm) in the upper and lower soil layer, $S_{s0(i)}$ and $S_{ss(i)}$ actual soil moisture storage (mm) in the upper and lower soil layer for day i, and $A_{max\_floodplain}$ the maximum extent of floodplain inundation during this particular flood.

At the top boundary of the control volume, water losses occur via evaporation. Open water evaporation was estimated as follows:

$$et_{ow(i)} = \frac{A_{open\_water(i)} \times e_{0(i)}}{1000} \quad (2)$$

where $et_{ow(i)}$ is floodplain and stream surface water evaporation (GL) for day i, $et_{0(i)}$ average potential evapotranspiration (mm) from AWRA-L v6 for day i, and $A_{open\_water(i)}$ floodplain and stream inundated area (km^2) for day i. The AWRA-L model does not account for open water evaporation from floodwater, hence we recalculated it in this study.

Local runoff entering the river reach and floodplain wetlands are also present. As the AWRA-L model does not simulate runoff generated by rainfall on overbank flows, total runoff in this study is estimated using the formula:

$$Q_{runoff(i)} = \frac{(q_{tot(i)} \times A_{not\_flood(i)} + P_i \times A_{flood(i)})}{1000} \quad (3)$$

where $Q_{runoff(i)}$ is total runoff (GL) generated across the study reach during day i, $q_{tot(i)}$ average runoff (mm) during day i, $A_{not\_flood(i)}$ the area not flooded (km^2) for day i, $A_{flood(i)}$ the flood area (km^2) of the study reach for day i and P_i average direct precipitation (mm) of the study reach during the day i.

The overall river reach water budget during a flood event is given by the following equation:

$$\sum_{i=1}^{n} Q_{upstream(i)} - \sum_{i=1}^{n} Q_{downstream(i)} = \Delta S_{wetting\_losses} + \sum_{i=1}^{n} et_{ow(i)} + \sum_{i=1}^{n} Q_{divert(i)} + \Delta S_{floodplain} - \sum_{i=1}^{n} Q_{runoff(i)} - e \quad (4)$$

where $Q_{upstream(i)}$ and $Q_{downstream(i)}$ is gauged river flow (GL) from upstream and downstream gauging stations for day i; $Q_{divert(i)}$ surface water diversions (GL) for day i, e unexplained residue.

3. RESULTS

A previous review of the Barwon-Darling River water sharing plan found that the bankfull river flow at Gauge A upstream is typically between 10,000 and 35,000 ML/d (Sheldon, 2019). We observed little difference in inundation extent across this interval, but water does spill onto the floodplain above 35,000 ML/d. Thus, the study area was split into the river and corresponding floodplain wetlands based on this threshold. When the river flow is 35,000 ML/d, the frequency of inundation is 1.4%, as estimated from the relationship between upstream discharge and Landsat-derived inundations at various frequencies. The distribution and volume of water in the river and floodplain are shown in Figs. 3 and 4. The monthly Pearson correlation between upstream gauged river flows and floodplain water volume dynamics from 1987 to 2020 is 0.94, indicating the reliable ability of the approach to estimate floodwater volume using Landsat and LiDAR observations. The maximum inundation areas in the river and floodplain during

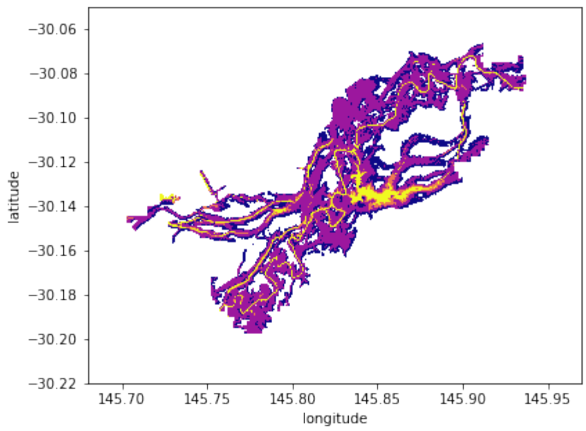

Figure 3. The inundation of the study reach at the river flow of 10,000 ML/d (yellow) and 35,000 ML/d (orange), and the maximum extent for the test flood event (yellow, orange and purple) and the maximum flood extent in historical observations (all colours).

the flood event between 20/12/2010 and 25/03/2011 were 10 km² and 42 km², respectively, conveying similar amounts of flood water (35 GL in river channels and 38 GL in floodplain wetlands) (Fig. 4).

Surface water diversion for irrigation is an important term in the water budget for this reach. Unfortunately, accurate data on water diversions are not available. We measured the extent of all reservoirs and on-farm dams in the study area using Landsat imagery. There are a total of seven levee dams and two reservoir dams (Fig. 1) in the study area, covering 16.43 km². Assuming a maximum levee height of around 4 m, the maximum possible water diversion to fill empty dams (i.e., maximum water storage) would be 65.73 GL, which was used as the maximum estimate for diversions, in line with the maximum estimates for other loss terms.

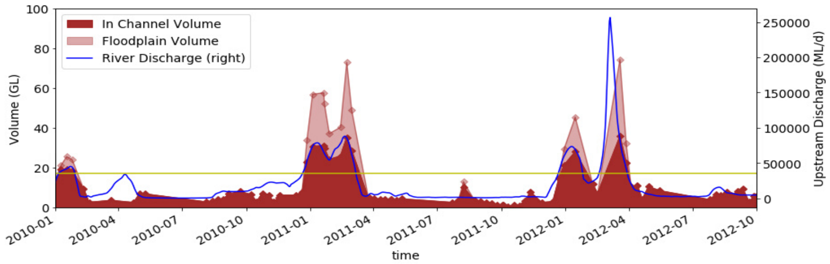

Figure 4. Time series of upstream river discharge (blue line) and water volumes in river channel (dark brown shade) and floodplain (light brown shade) between 2010 and 2012 (yellow line: overbank flow threshold)

AWRA-L simulations consider soil moisture replenishment by rainfall only. However, during the actual flood event, inundated soils would also be saturated by floodwater. On 20/12/2010, when the soil moisture deficit was 8.71 GL, overbank flow occurred, and this value was adopted as the amount of floodwater required to replenish soil moisture during the flood event. It is important to note that any rainfall after this date was assumed to run off. The estimated cumulative evaporation of floodplain and stream surface water during the flood event was 21.18 GL. Additionally, the total water volume generated from local runoff in the non-inundated area and direct rainfall on the inundated area during the flood event was 5.33 GL. As we developed this water budget for the period from the start of a flood event (when overbank flow occurs) to the end (when all floodwater returned to the river channel), there is no net change in floodplain water storage.

The water balance for the flood event was -9.15 GL, indicating that the total estimated losses exceeded the gains (Table 1). There could be several reasons for this imbalance. For example, our assumption that water diversion operated during overbank flows and that on-farm storages were empty when water diversion started might have led us to overestimate water diversions. We observed almost no change in the surface water extent of on-farm storages before and during the flood event, suggesting that they were not empty before the flood, even though water level increases are likely to have occurred. Another source of uncertainty in the water budget is the fact that we were not able to estimate the amount of water flowing towards the southwest on the floodplain and reconnecting to the river tens of kilometres downstream. Moreover, break-out flows were observed in the southwest of the study reach during this medium event, which could cause larger uncertainties in water budget accounting during larger flood events. Finally, the main inflows could be distributed to the bifurcated river channel beyond the main stem channel during the flood events, leading to an underestimation of the main stem inflows. Improving estimates of water diversion and ungauged flows during the flood event, as well as accounting for break-out flows and bifurcated channels, would help reduce uncertainties in the water budget.

Table 1. The overall river reach water budget, 20/12/2010 – 25/03/2011

Water budget	Accounts
Gains	GL
Main stem inflows	5367.29
Tributary inflows	-
Local inflows	5.33
Unattributed gains and noise	-
Losses	GL
Main stem outflows	5286.15
Distributary outflows	-
Floodplain storage change	0
Water diversions (maximum)	65.73
Open water evaporation	21.18
Wetting losses	8.71
Unattributed losses and noise	-
Unexplained residue	-9.15

4. DISCUSSION AND CONCLUSION

We developed a comprehensive framework for river reach water budget analysis by integrating gauging data, hydrological modelling, LiDAR DEM, and optical remote sensing. Details on the accuracy and uncertainties of the AWRA-L model and the satellite-based (Landsat-LiDAR) floodplain water extent, depth and storage estimates are provided in Frost and Wright (2018b) and Hou et al. (2022), respectively. The framework accounts for various hydrological variables, including main stem inflow, local runoff from non-flood areas, direct rainfalls on flood areas, main stem outflow, floodplain water volume change, floodplain and stream open water evaporation, surface water diversions, and the amount of water required to saturate soil water (i.e., wetting losses).

River water budget analysis can improve river modelling, particularly during flood events. We used AWRA-L modelling as an example, which does not consider flood inundation. Our reach water budget analysis can help correct local runoff and open water evaporation simulations from AWRA-L modelling by including vertical water fluxes between the atmosphere and floodwater. It also extends AWRA-L modelling capabilities to account for wetting losses, i.e., the flow volume required to replenish accumulated soil and groundwater deficits. By combining remote sensing technology and in-situ gauging measurements, we could estimate overbank flow onto the floodplain, the distribution of water on the floodplain, and return flows to the channel. However, we could not substitute the lack of data on river flows from tributaries and distributaries or surface water diversions other than being able to establish that they likely did occur. Upon manually checking the Landsat-derived surface water mapping at the basin scale, we found that there could be a significant amount of water flowing downstream from the southwestern channels of the study reach during flooding events.

In addition to the gauging data, we also examined downstream outflows and upstream inflows. Our analysis revealed that the downstream gauging station B may have overestimated low flows in the study reach during dry periods. To address this, we considered data from a second downstream gauging station, C, located approximately 7.6 km away from station B. However, the data from station C suggested that it may underestimate river flow at certain times. Despite our efforts to account for these discrepancies, we could not find evidence of tributaries or distributaries along the 7.6 km section of the river between stations B and C. As a result, we used the average discharge from the two gauging stations to estimate outflows for the study reach. The difference in an absolute deviation between the two downstream gauging stations was 1288 GL, which translates to 29–37% uncertainty in the estimated outflows for stations B and C, respectively. We conclude that the uncertainties in the gauged outflows for this study region were around 29–37%. The unexplained residual term in the water budget was within that range, indicating that the water balance closure was as good as can be expected for this flood event.

We could not access in situ water use data and therefore assumed that all on-farm storages and reservoirs were empty before the flood event and full after it. This assumption introduced large uncertainties in the water budget. Although we used Landsat to measure changes in water extent in these dams, the measured water extent were not sensitive to storage changes due to the steep levee slopes and relatively low resolution of the Landsat imagery. Higher-resolution imagery or satellite altimetry could be used to detect elevation changes in these water bodies. For example, Topex/Poseidon (1992-2002), Jason-1/-2/-3 (2002-present), and Jason-CS/Sentinel-6 (2020-present) can be combined to derive water elevation changes in surface water bodies with a frequency of 10 days over the past 30 years. However, the sparse path of these satellites makes them less likely to capture small dams. Alternatively, ICESat-2 has much denser coverage of global surface water bodies, which makes it possible to measure the elevation changes in Australian on-farm dams and reservoirs. The drawback is that ICESat-2 has a 90-day temporal resolution, which limits its ability to identify short-term changes (e.g., 10 days) and can only detect seasonal changes. Overall, integrating these satellite altimetry data and LiDAR-derived DEMs could enhance the accuracy of estimating small on-farm storages.

The Landsat observations utilised in this study were limited by dense cloud covers during flood events and the satellite's low temporal frequency (16-day), which reduced the chance of capturing flood events. For instance, the large flood event in March 2012 was not captured due to cloud issues (Fig. 4). Sentinel-1 and -2 are potential alternatives that can be used to estimate flood water volume changes. Sentinel-2 has a high spatial and temporal resolution (10-m and 5-day) but is still affected by clouds. Sentinel-1 may be a better option due to its Synthetic Aperture Radar (SAR), which can detect flood events during all weather conditions and at any time of day or night. The Surface Water and Ocean Topography (SWOT) mission should also help to measure water volume changes in floodplains directly, as it simultaneously measures surface water elevation and extent.

The reach water budget analysis framework developed in this study can potentially be applied to different flood events and regions across Australia. However, the water budget framework developed here did not account for evapotranspiration from different vegetation communities on the floodplain wetlands. The 30-m actual evapotranspiration (AET) dataset for Australia using the CMRSET algorithm (Guerschman et al., 2022) could be useful for estimating the water use of floodplain vegetation. Furthermore, a sensitivity analysis would likely help gain deeper understanding of the uncertainties associated with each estimated item in the reach water budget. Overall, the reach water budget analysis could be a valuable tool for assessing water availability and management at the catchment or basin scale. It can be used to estimate unknown hydrological components (e.g., Hou et al., 2022) or validate simulations (e.g., Bhattarai et al., 2019) and as such be a versatile method for advancing our understanding of water resources.

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