Mapping stream surface flow types by balloon: an inexpensive high resolution remote sensing solution to rapid assessment of stream habitat heterogeneity?

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Abstract Spatial variation in hydraulic conditions in streams often results in distinct water surface patterns, or surface flow types. Recent studies have demonstrated that these surface flow types represent a distinct suite of hydraulic conditions with biological relevance, highlighting the potential value of surface flow type mapping as a rapid method for assessing hydraulic habitat heterogeneity in streams. Traditional approaches to surface flow mapping have used stream bank visual assessment of the presence and extent of flow type within assessment reaches. Such methods are subject to assessor bias and, particularly in larger streams, difficulties in assessing areal extent from strongly oblique views. This study uses a high resolution remote sensing approach to map surface flow types. The approach uses a balloon-mounted digital video recorder to record images of study reaches in plan view at a height of approximately 12 m. Ortho-rectified images are then used to identify surface flow types and digitise their extent. Areal extents of surface flow types derived through this process in a trial study were compared to those derived from streamside visual assessment to provide a preliminary test of the efficacy of the approach.

Key words hydraulic habitat; surface flow types; remotely sensed data; river habitat heterogeneity

INTRODUCTION

Flow is of fundamental importance to aquatic biota (Davis & Barmuta 1989; Quinn & Hickey, 1994; Hart & Finelli, 1999; Finelli *et al.*, 2002; Biggs *et al.*, 2005; Brooks *et al.*, 2005). In conjunction with the nature of the river-bed substratum, which itself influences and is influenced by hydraulic conditions (Davis & Barmuta 1989; Young 1992; Rempel *et al.*, 2000; Emery *et al.*, 2003), the range of hydraulic conditions present within a stream is fundamental to the physical habitat template affecting instream biota (Hart & Finelli 1999; Rempel *et al.*, 2000).

Water depth, roughness and slope are principal determinants of hydraulic conditions within river channels. Variation in these parameters results in spatial and temporal heterogeneity in hydraulic conditions. Where gradients are sufficiently large, this heterogeneity results in clear differences in water surface features known as “surface flow types” (SFTs). Eight surface flow types have been identified based on visual assessment (Newson & Newson, 2000). It has been argued that surface flow types can be used to rapidly determine the level of spatial heterogeneity in hydraulic conditions in streams (Newson & Newson, 2000), and recent studies have demonstrated the biological relevance of these features (Dyer & Thoms, 2006; Reid *et al.*, 2006; Reid & Thoms, 2008). Published studies that have used surface flow types to assess levels of spatial heterogeneity in streams, have used stream bank visual assessment of the presence and extent of flow type within assessment reaches. Such methods are subject to assessor bias and, particularly in larger streams, difficulties in assessing areal extent from strongly oblique views. Alternatives such as high resolution aerial photography require costly imagery and may not provide sufficient resolution to distinguish all surface flow features. This study examines the utility of an alternative approach which uses a balloon-mounted digital video recorder to record images of stream reaches in plan view at a height of approx. 12 m.

METHODS

Study area

The Cotter River is an upland cobble/gravel bed river situated in the eastern highlands of Australia (Fig. 1). The study reach is a fourth-order stream reach that spans an altitudinal range from 700 m

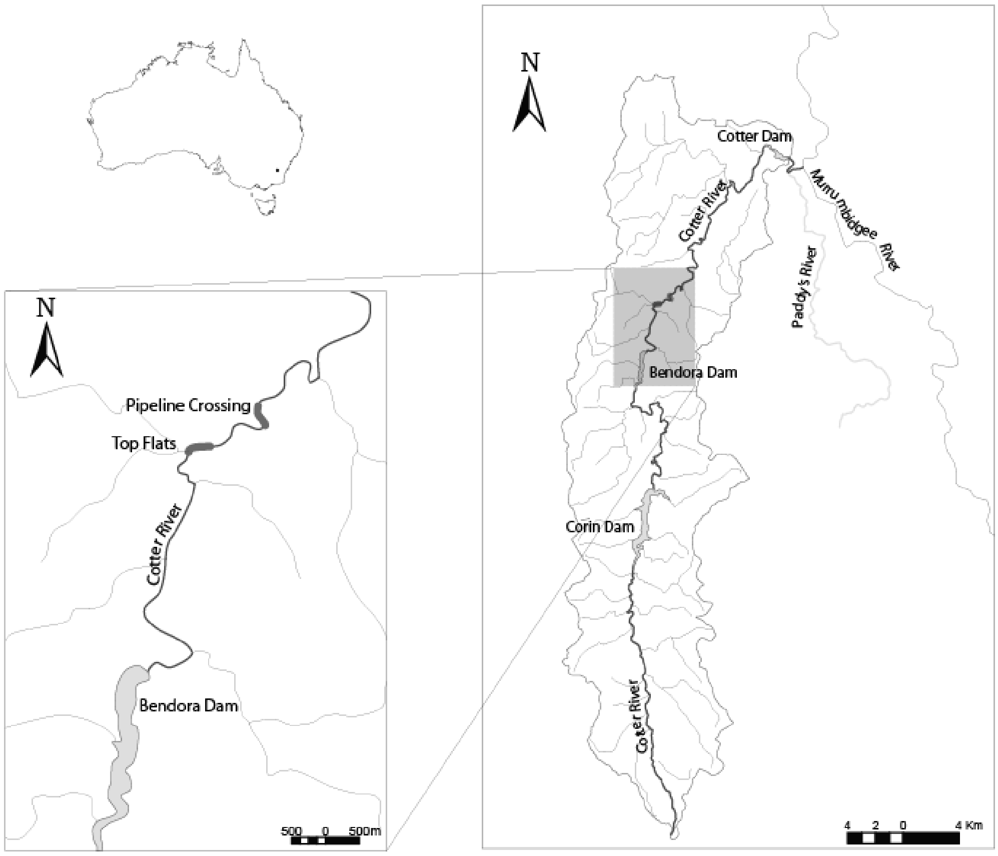

Fig. 1 Locations of study reaches on the Cotter River.

to 500 m above mean sea level; its catchment is largely unmodified by humans and is mostly forested, with 88% lying within the Namadgi National Park. The underlying geology is a mix of granite, limestone, siltstone and shale. Catchment topography is steep, with rock outcrops common, particularly at higher altitudes. The climate is temperate with hot summers and cold winters. Average precipitation ranges from 990 mm to 1080 mm. The wettest months are between July and October.

Three dams that supply water for the city of Canberra (population approx. 322 000) regulate flow in the river. Environmental flow releases designed to minimize the impact of the dams by providing key elements of the natural flow regime are made, although these releases are constrained by water supply requirements.

METHODS

The study was carried out in the Cotter River at two reaches situated between Bendora and Cotter Dams: a reach of approx. 200 m (Top Flat) and a reach of approx. 250 m (Pipeline Crossing) (Fig. 1; Table 1). Data were collected during the austral summer of 2004 in a period of controlled releases from Bendora Dam, and used to quantify the spatial extents of surface flow types (SFTs) within the two reaches under two different flows. Airborne multi-spectral digital imagery was obtained in conjunction with field measurements on 21 January at Top Flat and at Pipeline Crossing on 28 January at a discharge of 30 ML/day. Data were collected on a second occasion at the higher discharge of 100 ML/day on 18 February at Top Flat and on 23 February at Pipeline Crossing.

A helium balloon (4.5 m × 2.8 m × 1.8 m) fitted with a JVC GR-DVL520 digital colour night scope camera with Digital Video Input/Output was flown at a height of 10 m over the study

Table 1 Site characteristics.

Site	Location (AGD 66)	Average bed slope	Dominant river bed substratum	Major in-channel geomorphic units
Top Flats	0666413 E 6079289 N	0.011	Boulder cobble and bedrock	Pools, riffles. Chutes and mid-channel bars
Pipeline Crossing	0669363 E 6082249 N	0.003	Cobble and gravel	Pools and riffles

reaches on each occasion. At the same time as images were being captured, three experienced observers visually identified SFTs and estimated their extent as a percentage of the total surface area of the stream within 50 m subsections of each reach.

The digital images were formatted as an Mpeg1, Muxed 320 × 240 pixels file format at a resolution of 7.5 cm/pixel across all four base images. Still images were captured from the Mpeg files and sorted sequentially. Digital panoramas of the river were created using Scale Invariant Feature Transform (SIFT) function in "Autostitch" (Brown & Lowe, 2003). The SIFT function combines feature matching, image matching, bundle adjustment, multi-band adjustment and a probabilistic model for image match verification (Brown & Lowe, 2002, 2003). A total of 3047 individual images were assembled into 30 panoramas, then assembled sequentially into four base images, one for each reach at each discharge; these images were then imported into ArcGIS and ER Mapper for spatial analysis.

The base images were ortho-rectified by selecting 20 ground control points (GCP) from the base images and identifying those GCPs on ortho-rectified Cotter Catchment Aerial Photography captured on the 15 February 2005 by Geoscience Australia. ArcGIS Shape files were constructed to outline the images and vegetation, and rocks that were in the river channel were colour coded and shape files were constructed to remove them from the final flow analysis layer. Due to the differences in total area and the volume of water at the time of the data collection, these shape files varied in size between images. This was done so that we could have an image of just the surface of the water with minimal distortion.

SFTs in each base image were then identified and the area of each within the 50 m subsections corresponding to those used in the ground-based visual estimations calculated in ArcGIS.

RESULTS

Six different SFTs were identified in the study reaches in both the ground-based surveys and through interpretation of aerial images (Table 2). SBT was the most extensive SFT under both low and high flow conditions and by both ground observation and aerial image interpretation (Fig. 2).

Table 2 Surface flow types identified in the Cotter River study reaches by ground-based observation and remote sensing (adapted from Newson & Newson, 2000).

Surface flow type	Code	Definition
Broken standing waves	BSW	Standing waves present with white water. The general direction of the crest is upstream. The face of the crest was undetectable in the images examined.
Unbroken standing waves	UBSW	Standing waves present without broken (white) water. The crest of the wave faces upstream.
Ripple flow	RF	Water surface has regular distribution of disturbance across the surface. Ripples appear to move in a downstream direction.
Chute flow	CF	Fast, smooth boundary turbulent flow over boulders and bedrock. Flow is in contact with the substrate. This flow is typically being funnelled by macro bed elements
No perceptible flow	NPF	Smooth surface, suspended matter and surface foam appear stationary.
Smooth boundary turbulent	SBT	Flow in which relative roughness is so low that little surface turbulence occurs. Reflections are distorted and surface foam moves in a downstream direction

NPF and RF were also common, but the extent of each of these SFT varied with discharge. In the case of NPF, its extent declined during high flow, while for RF the change in relation to discharge depended on the estimation method, with an increase in extent with discharge evident for ground-based observation, but little change or a slight decline evident with increased discharge when estimations were based on aerial image interpretation. USW, BSW and CF were all less extensive in the study reaches, and with the exception of BSW which became more extensive under high discharge, did not change greatly in their areal extent in response to changing discharge.

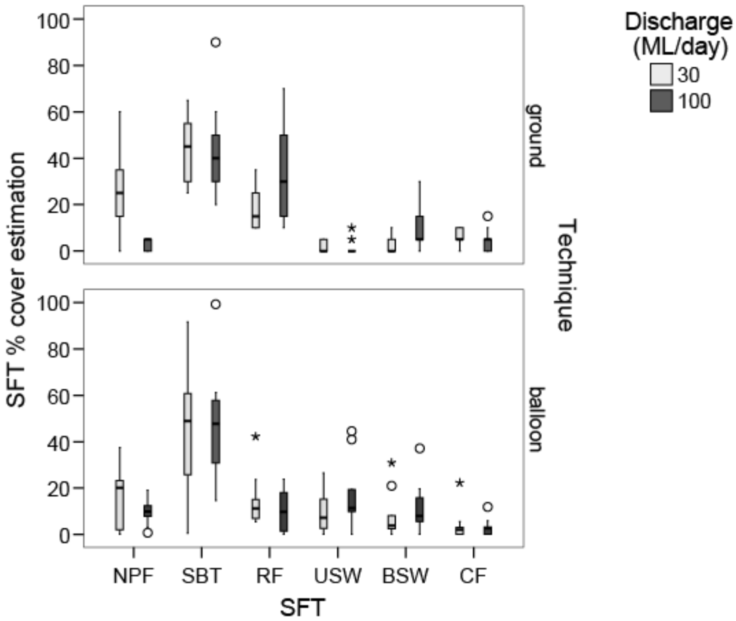

Fig. 2 Box plots showing % cover of SFTs within reach subsections for both study reaches under low (30 ML/day) and high (100 ML/day) flow conditions estimated from ground observations (ground) and aerial image interpretation (balloon).

Table 3 Results of 3-factor ANOVA comparing the difference between aerial image interpretation estimates and ground-based estimates of percent cover of SFTs across discharges, SFTs and reaches.

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	2.04E-005	1	2.04E-005	3.645	0.307
	Error	5.60E-006	1	5.60E-006(a)		
Discharge	Hypothesis	5.60E-006	1	5.60E-006	0.274	0.693
	Error	2.04E-005	1	2.04E-005(b)		
SFT	Hypothesis	6540.799	5	1308.160	8.431	0.018
	Error	775.818	5	155.164(c)		
Reach	Hypothesis	5.60E-006	1	5.60E-006	0.000	1.000
	Error	31.034	0.525	59.125(d)		
Discharge * SFT	Hypothesis	3398.500	5	679.700	7.077	0.026
	Error	480.194	5	96.039(e)		
Discharge * Reach	Hypothesis	2.04E-005	1	2.04E-005	0.000	1.000
	Error	480.194	5	96.039(e)		
SFT * Reach	Hypothesis	775.818	5	155.164	1.616	0.306
	Error	480.194	5	96.039(e)		
Discharge * SFT * Reach	Hypothesis	480.194	5	96.039	0.268	0.929
	Error	30084.097	84	358.144(f)		

a, MS(Reach); b, MS(Discharge * Reach); c, MS(SFT * Reach); d, MS(Discharge * Reach) + MS(SFT * Reach) – MS(Discharge * SFT * Reach); e, MS(Discharge * SFT * Reach); f, MS(Error).

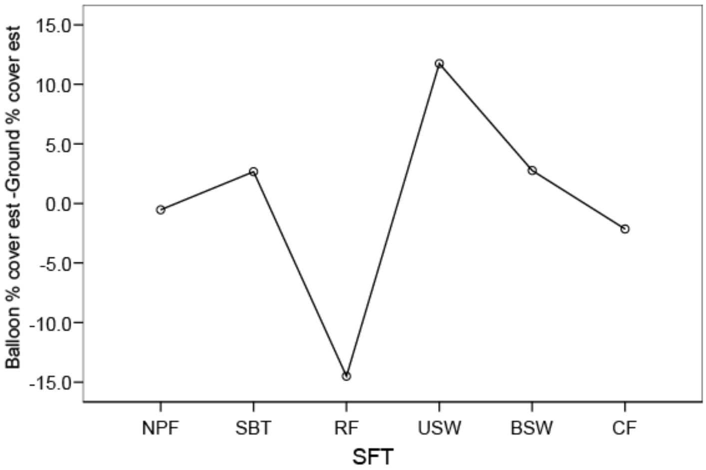

Fig. 3 Estimated marginal means for estimation disparities by flow type.

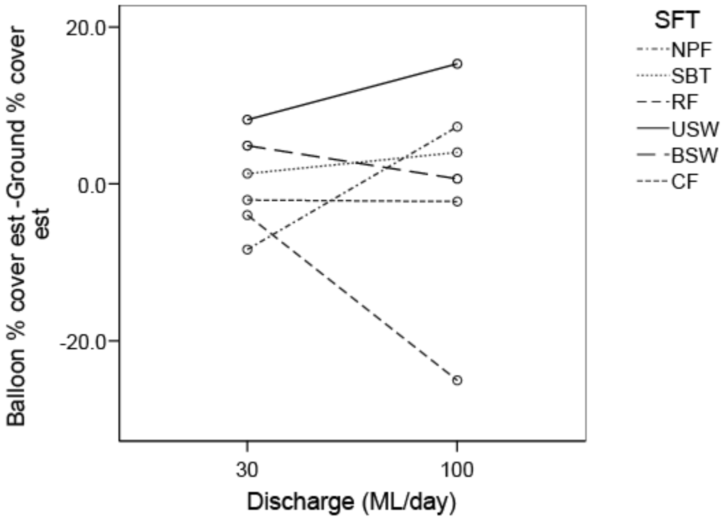

Fig. 4 Estimated marginal means for estimation disparities by flow type and discharge.

Although overall there was a good agreement in the SFT cover estimates based on ground observation and aerial image interpretation, as indicated by median values for the difference between these estimates being close to zero for most SFTs (Fig. 3), the disparities in these estimates did vary significantly according to SFT (Table 3; Fig. 3). This result reflects the substantially higher ground-based estimates of RF cover compared to estimates from aerial image interpretation and reverse pattern that is evident for USW. The degree of disparity between estimates also varied according to discharge (Fig. 4). Accordingly, the disparity in RF and, to a lesser extent USW, cover estimates became greater with higher discharge. An interaction with discharge was also evident for estimates of the extent of NPF whereby ground-based estimates were substantially higher than aerial image interpretation estimates at low discharge cover, but substantially lower at high discharge.

DISCUSSION

Overall there is good agreement between the two estimation methods. This suggests that, with further development, the use of aerial imagery to estimate the areal extent of SFTs may prove an effective means to assess spatial and temporal heterogeneity of hydraulic habitat in streams. There are several advantages of aerial image interpretation over ground-based visual estimates. First, the use of digital images allows for more precise calculation of the surface area of each flow type than ground-based visual estimates. Second, the images themselves provide permanent raw data that can be scrutinised at a later date and provide comparable time series data. Third, the outputs of the analysis are digital spatial data which confer the capacity to apply more complex spatial analysis to characterise the heterogeneity of the hydraulic environment in terms of the spatial mosaic of SFTs present in streams or stream reaches of interest.

There are aspects of aerial image interpretation approach applied here that need refinement. The results show substantial disparities between ground-based estimates and estimates based on aerial image interpretation, most notably for RF and USW areas. It is possible that the disparities reflect inaccuracies in estimates of the extent of each SFT by ground observers, that is, in comparison to the more precise calculations that were made through spatial analysis of the digital imagery; however, the fact that the greatest disparities were for RF and USW suggests that they result principally from the assignment of areas categorised in ground-based estimates as RF as USW in estimates based on aerial image interpretation. The distinction between these two flow types is perhaps the most subjective, given that both SFTs are characterised by the presence of surface undulations in the absence of "white water", with the main distinction being in the size of those undulations (Newson & Newson, 2000). Accordingly, it would seem that improvements to the methods of estimating SFT extent through interpretation of aerial images should focus on ways of ensuring operators are able to reliably distinguish between RF and USW areas in aerial images through ground validation and calibration. This task may primarily require improved resolution in imagery, or increased operator experience, or both. Further studies directed specifically at this task are required to advance this method as a viable alternative to ground-based estimates of the extent of SFTs, but the advantages of the approach – greater precision, accuracy and analytical scope – mean that such studies would be most valuable.

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