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Estimating Volume of Water Harvested by Farm Dams in Murray-Darling Basin

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Abstract: With limited water resources available, farmers in many parts of Australia have resorted to building farm dams to supplement water for irrigation and stock. While the impact of an individual farm dam on a catchment is relatively small, the cumulative impact on runoff from a large number of farm dams on may be significant. To give an example of scale, the Murray-Darling Basin (MDB) has over 650,000 farm dams at present. This paper aims to quantify the effect of the farm dams on the water resources in the Murray–Darling Basin.

Through the Water Act 2007, the Bureau of Meteorology (the BoM) has the responsibility to produce an annual National Water Account (NWA) which provides information on water stores and fluxes, water rights and water use across Australia. The Australian Water Resource Assessment Modelling System (AWRAMS) is being developed by CSIRO and the BoM through the Water Information Research and Development Alliance (WIRADA) initiative. AWRAMS is a new integrated continental hydrological simulation system that has two modeling components to represent processes between the atmosphere and the landscape (AWRA-L) and in gauged rivers (AWRA-R), including all major water storages and fluxes in and between these components (surface, subsurface and groundwater). One of the fluxes described in the NWA is the runoff to rivers/reservoirs accounting for interception and storage by farm dams.

The Spatial Tool for Estimating Farm Dam Impacts (STEDI), developed by SKM, was used in the production of the NWAs for 2010 and 2011. STEDI carries out a water balance for each farm dam at each monthly time step using contributing catchment inflows, rainfall, evaporation and on-farm demand. The contributing catchment inflows were obtained by lumping the contributing catchment's runoff generated by the grid-based AWRA–L model. Running the STEDI model is time consuming in terms of preparing and inputting the data into the model and applying it over large areas as the number of farm dams in a model run must be less than 10,000 (requiring 105 regions in the case of the MDB). In order to streamline and speed up the production of the NWA, a farm dam model (FDM) similar to STEDI was coded in FORTRAN, run over the NWA Canberra region and then evaluated by comparing the results to those from the original STEDI model. Following successful evaluation, the developed FDM model was applied to the recent NWAs (NWA 2011, NWA 2012, NWA 2013 and NWA 2014) over the MDB.

The current FDM approach used in the NWA has two limitations: all farm dams are assumed to be directly connected to the catchment outlet and the spatial variation in the input is ignored by lumping them. Also, currently the farm dam modelling is undertaken separate from the AWRAMS although there are plans to integrate the two in the future. This paper will present the development of a farm dam model and its application to the MDB for the production of the NWA reports. Future direction of farm dam modeling through model integration with the BoM's operational AWRAMS is also presented at the end of the paper.

Keywords: *Farm dam modelling, water harvesting, National Water Account, Murray-Darling Basin*

1. INTRODUCTION

Australia is often considered the driest inhabited continent in the world, yet it has much variability in water availability with areas ranging from water rich to water scarce. The Murray Darling Basin (MDB) is the largest river basin in Australia and is generally considered its 'food bowl' due to its important agricultural production. The MDB suffered a prolonged drought from 1997-2009 known as the millennium drought, during which rivers within the MDB received 40 percent less inflow than was the long term average (Saha, 2015). In order to overcome the water scarcity, many farmers constructed small farm dams with volumes approximately ranging from 0.2 to 100 ML (CSIRO, 2007). Farm dams are typically earth structures designed to capture and store water for irrigation, aquaculture, stock watering, domestic supply or aesthetic purposes (Lewis, 2002). These farm dams have been shown to store up to 2,168 GL of water in the Basin and can act as a significant interceptor to runoff, potentially reducing stream flow (SKM, 2007). Reduced streamflow in the rivers can affect the health of many precious riparian flora and fauna that live in or near the river. SKM (2007) have carried out a study projecting new farm dams to 2030 and assessed the future impact of farm dams on runoff in the MDB. The findings of the study are the volume of water stored in farm dams will increase to 2428 GL (net increase of 228 GL) and runoff to rivers and storages will be reduced to 180 GL in 2030. Considering high competition among various sectors for scarce water, there is an urgent need to monitor water flows and usage more carefully for agriculture production within the MDB.

Knowledge of the hydrology on irrigated farms within the inundation plains of the MDB is limited in quality, and reliability of the observation network that has been declining rapidly over the past few decades (Hafeez et al., 2011). While the impact of an individual farm dam on a catchment is relatively small, the cumulative impact of a large number of farms on runoff may be significant. As an example of scale, the MDB has over 650,000 farm dams at present (Leslie, 2005). It therefore becomes necessary to quantify the effect of farm dams on the water resources. Improved estimates of the volume of water stored in farm dams will guide water management decisions at farm to catchment scale and could be instrumental for enhancing the integrity of the water allocation process and making it more fair and equitable across stakeholders in the MDB. Since 2008, Australian Government has been buying back water entitlements from individual farmers to maintain environmental flows and to secure water for cities as part of the Water Smart Australia initiative.

Accurate estimation of the volume of water stored in the small dams scattered around the MDB is complex and scientifically challenging. Traditionally, volumes of water stored in farm dams are estimated by conducting a bathymetric survey of each farm dam but this is time consuming and costly (Hafeez et al., 2007). Remote sensing-based volumetric assessment of water stored in farm dams has been successfully applied in Australia and overseas (Hafeez et al., 2007, Chemin and Rabbani, 2011) using high spatial resolution satellite imagery, however this needs to be coupled with either bathymetric survey or a high resolution digital elevation model to derive depth-area-volume relationships for accurate volume estimation.

In Australia, many operational water balance models have been developed to estimate volumes of water stored in farm dams for various catchments. Each model has its merits and weaknesses. A starting point was the Tool for Estimating Dam Impacts (TEDI model) developed by ICAMC and SKM (1999), a simple computer program that assesses the impacts of farm dams on streamflow at catchment scales. However, the TEDI model cannot represent farm dams spatially in the catchment. To overcome this limitation, the Complete Hydrological Evaluation of the Assumptions in TEDI (CHEAT model) was developed by Nathan et al. (2005) using a spatially explicit network of all farm dams in a study catchment. Building on the CHEAT model functionality, SKM later developed the Spatial Tool for Estimating Dam Impacts (STEDI model), a Windows-based computer program for simulating the impact of farm dams on streamflows within the MDB (SKM, 2011). The STEDI model allows the user to spatially configure a network of dams in any catchment so that inflows are influenced by upstream dams. The STEDI model has been primarily used as an input to larger surface water models like REALM and SOURCE.

Most recently, the Bureau of Meteorology (the BoM) has developed an operational daily water balance model called the Australian Water Resources Assessment Modelling System (AWRAMS), a new integrated continental hydrological simulation system which is mainly used for water accounting and water resources assessment purposes (Hafeez et al., 2015). The AWRAMS has two modeling components that represent processes between the atmosphere and the landscape (AWRA-L) and processes in gauged rivers (AWRA-R), including all major water storages and fluxes in and between these components (surface, subsurface and groundwater). In order to estimate the volume of water stored in farm dams, the BoM team has developed a farm dam model (FDM) coded in FORTRAN that is conceptually similar to STEDI and mainly used for water accounting purposes in the MDB. One of the important fluxes in the National Water Account (NWA) is the runoff to rivers/reservoirs accounting for interception and storage by farm dams.

The purpose of this paper is to use the FDM model to estimate farm dam water storage volumes within selected catchments of the MDB and compare this with the estimate from the STEDI model.

2. STUDY AREA

The MDB, the study area, is the catchment of the Darling (2,740 km) and Murray (2,520 km) Rivers including their tributaries and is located in the south east of Australia. The MDB is the largest river basin in Australia, covering one seventh of the mainland and falling within Queensland, New South Wales, Victoria, South Australia and the Australian Capital Territory. The MDB contains 40 percent of Australia's farms, 65 percent of its irrigated land and produces one-third of the national food supply (MDBA, 2014). The gross value of irrigated agricultural production was $4,349 million in 2008-09 and increased to $6,691 million in 2011-12 following the end of the Millennium drought in 2010 (MDBA, 2014). The region has a population of over 2 million, and irrigated agriculture is a major industry. The MDB has been divided into 19 catchments for managing surface water resources as shown in Figure 1. The more than 650,000 farm dams in the MDB (Figure 1) are mainly used for irrigation purposes. Long term average rainfall (1900-2014) is 470 mm which varies widely from northern catchments to southern catchments. Annual rainfall ranges from more than 1,200–1,800 mm across the southern areas of the region to less than 300 mm in the west (BOM, 2014).

The NWA Canberra region is located in the southeast of Australia and within the MDB. It is home to approximately 426,000 people and covers an area of 4,202 km² (BoM, 2015). The region is characterized by forested mountains in the south and west of the region and plains in the north. The Murrumbidgee River is the main waterway running through the region and its tributaries within the NWA Canberra region include the Cotter, Gudgenby, Molonglo and Queanbeyan Rivers. The long-term average rainfall within the region is about 794 mm (period 1900-2014). In terms of water resources management, the NWA Canberra region has significant importance to the city of Canberra, the largest urban center within the MDB.

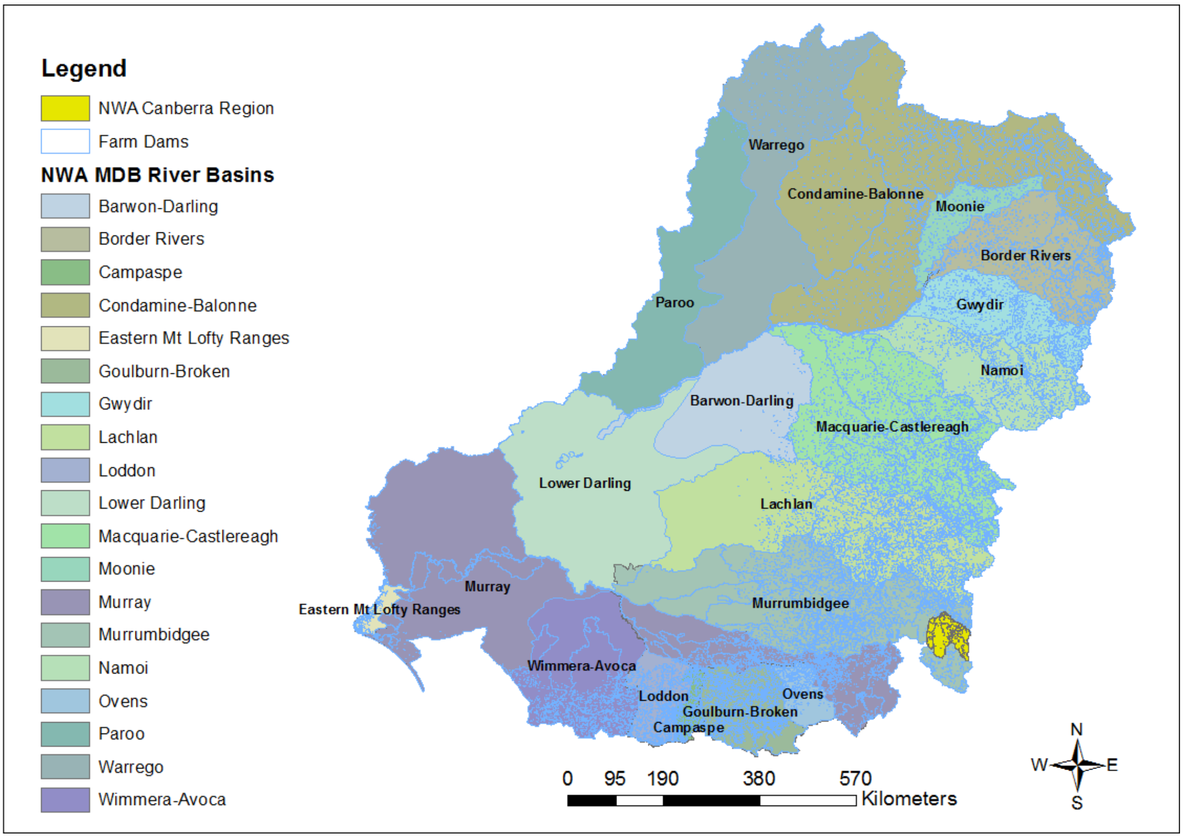

Figure 1. Catchments within the Murray Darling Basin

3. METHODOLOGY

The STEDI model (SKM, 2011) was used during the production of NWAs in 2010 (BoM, 2011) and 2011 (BoM, 2012). This tool was used to assess the effect of farm dams on runoff, and can generally handle up to 10,000 farm dams per model. The STEDI tool uses a graphical user interface that makes it time consuming to input data and post-process outputs for the NWA, especially when users need to deal with the tens of thousands of farm dams covering a large area such as Murray Darling Basin (MDB). It was decided to develop a farm dam model (FDM) that adopted a similar concept to the STEDI model but overcame these limitations.

The FDM developed in this paper is a water balance model of farm dams. The inputs to this model are rainfall, evaporation, catchment runoff and demand. Like the STEDI model, spill from any farm dam in the catchment is assumed to flow directly to the catchment outlet. Index j is used to represent whether the farm dam is used for stock and domestic (j = 1) or for irrigation (j = 2). A capacity threshold (C_{th}) is used to determine the type of dam use. If the capacity of the farm dam is greater than C_{th} then it is assumed to be used for irrigation. Otherwise, it is assumed to be used for stock and domestic purposes. The water balance of farm dam i for month t is given as follows:

$$S_i(t) = S_i(t\text{-}1) + Q_t\, CA_i + R_t SA_i - E_t SA_i - Use_i(t) \qquad (1)$$

where,

$S_i(t)$	Water storage in farm dam i for month t (ML)
$S_i(t\text{-}1)$	Water storage in farm dam i for month t-1 (ML)
Q_t	Catchment average runoff for month t (mm)
CA_i	Catchment area contributing to farm dam i (Km^2)
R_t	Catchment average rainfall for month t (mm)
SA_i	Surface area of farm dam i (Km^2)
E_t	Catchment average evaporation for month t (mm)
$Use_i(t)$	Water use for month t (= $ODF_{jk}C_i$) (ML)
C_i	Capacity of farm dam i (ML)
ODF_{jk}	Overall demand factor for use types j and k (k = 1 water use, k = 2 seepage loss)

Subject to the following conditions:

If $S_i(t) > C_i$ $\quad Spill_i(t) = S_i(t) - C_i$ and $S_i(t) = C_i$

where, $Spill_i(t)$ is the spill from farm dam i

If $S_i(t) < 0$, $\quad Use_i(t)^* = Use_i(t) + S_i(t)$ and $S_i(t) = 0$

If $Use_i(t)^* < 0$, $\quad Evap_i(t)^* = Evap_i(t) + Use_i(t)^*$ and $Use_i(t)^* = 0$

If $Evap_i(t)^* < 0$, $\quad Evap_i(t)^* = 0$

$$\text{Total runoff with no farm dams} = Q_t A \qquad (2)$$

where, A is the total catchment area (km^2)

$$\text{Total runoff with farm dams} = \max\left(Q_t(A - \sum CA_i), 0\right) + \sum\sum Spill_i(t) \qquad (3)$$

$$\text{Runoff harvesting} = Q_t \sum CA_i - \sum\sum Spill_i(t) \qquad (4)$$

$$\text{Precipitation of off-channel storages} = \sum R_t \sum SA_i \qquad (5)$$

$$\text{Evaporation from off-channel storages} = \sum\sum Evap_i(t) \qquad (6)$$

$$\text{Water use} = \sum\sum Use_i(t) \qquad (7)$$

$$\text{Spill} = \sum\sum Spill_i(t) \qquad (8)$$

Each farm dam is modelled separately and aggregated over the catchment to obtain the total stored water volume. At the start, all farm dams are assumed to be empty. Runoff from the contributing area and rainfall falling on the farm dam are added while water use and evaporation from the farm dam are subtracted from the starting storage of the dam. At the end of each time step, there are three possibilities.

1. Storage value lies between zero and the capacity of the farm dam; proceed to the next time step.

2. Storage value is greater than the capacity of the farm dam; farm dam spills and the storage is set to the capacity of the farm dam.
3. Storage value is less than zero; water in the dam is not sufficient to meet the evaporation and water use demand. Demand is first reduced so that the storage becomes zero. If this is not enough to bring the storage to zero, then the evaporation is reduced so that the storage is become zero.

The above procedure is repeated for all time steps where input data are available.

4. RESULTS AND DISCUSSION

The developed FDM was applied to the NWA Canberra region (BoM, 2015) so as to compare with results obtained from the STEDI model for 2010-11 and 2011-12. Due to the limitation on the maximum number of farms dams that can be represented in the STEDI model, the Canberra region was divided into five sub-regions to run. The results from each model are presented in Table 1 both for the five sub-regions and for the whole region.

Table 1. Comparison of the results from the STEDI and FDM

Catchment		Bendora	Canberra downstream	Corin	Cotter	Googong	Total
Off-channel water storages (ML)							
2010-11	STEDI	29	6648	4	9	1409	8098
	FDM	29	6656	4	9	1412	8110
2011-12	STEDI	29	7025	4	9	1455	8522
	FDM	29	7034	4	9	1458	8534
Precipitation on off-channel water store (ML)							
2010-11	STEDI	19	5189	7	15	1136	6365
	FDM	19	5188	7	15	1136	6364
2011-12	STEDI	18	5164	6	14	1185	6387
	FDM	18	5164	6	14	1186	6387
Runoff harvesting into off-channel water store (ML)							
2010-11	STEDI	29	5609	-1	-1	915	6551
	FDM	29	5644	-1	-1	915	6586
2011-12	STEDI	7	3764	-1	0	676	4447
	FDM	7	3792	-1	0	676	4475
Evaporation from off-channel private storages (ML)							
2010-11	STEDI	11	4634	3	9	1042	5699
	FDM	11	4636	3	9	1042	5701
2011-12	STEDI	11	4617	4	9	1052	5693
	FDM	11	4624	4	9	1053	5701
Water use (ML)							
2010-11	STEDI	14	4128	2	5	791	4939
	FDM	14	4134	2	5	791	4946
2011-12	STEDI	14	3931	2	5	762	4714
	FDM	14	3931	2	5	762	4715

Table 1 shows that the results from the developed FDM model are similar to those from the STEDI model which provides confidence. The differences between the results from the two models are small and the largest percentage difference is 0.6 percent for the whole Canberra region. Based on this evaluation, the Bureau decided to use the FDM model to estimate the volume of water stored in farm dams within the entire MDB for NWA purposes.

To model the whole of the MDB it was divided into 105 regions for the purposes of modelling the farm dams. The AWRA-L model input and output provided catchment average rainfall, evaporation and runoff which were calculated for each of the 105 regions as the mean occurring across the relevant grid points within the region boundary. Points were weighted by the area they represented to remove edge effects (where the area represented was not wholly within the MDB region) and the effect of changing area represented with changing latitude. The FDM was applied to NWAs for four time water years (i.e., 2010-11, 2011-12, 2012-13 and 2013-14). The results of the 18 modeled catchments are presented in Table 2. It should be noted that modeling was not done for the Lower Darling as there were no farm dams represented in the available data for this region. The lowest number of farm dams appears in the Paroo catchment and the highest number occurs in the Macquarie-Castlereagh catchment. Rainfall appears to be the main factor affecting the magnitude of the values in Table 2. It can be seen from Table 3 that a large volume was harvested each year in farm dams, ranging from 1,004 GL (in 2013-14) to 1,516 GL (in 2010-11). It can also be noticed in Table 3 that there was considerable water use from the farm dams, ranging from 710 GL (in 2013-14) to 1,107 GL (in 2010-11). This shows that farm dams have a significant impact on managing scarce water resources in the MDB.

Table 2. Results of various catchments in MDB using the FDM

Region	Barwon Darling	Border Rivers	Conda-mine Balonne	Gwydir	Macquarie Castle-reagh	Moonie	Namoi	Paroo	Warrego	Campaspe	Eastern Mount Lofty Ranges	Goulburn Broken	Loddon	Murray	Murrum-bidgee	Oven s	Wimmera Avoca	Lachlan
(a) Off-channel water storages (ML)																		
2010-11	2,492	56,857	156,327	34,992	158,212	21,293	57,108	536	25,534	24,906	11,304	99,205	41,215	59,998	158,443	33,315	40,356	149,845
2011-12	2,810	57,253	140,142	52,677	168,615	21,738	64,007	598	26,396	20,990	11,879	96,181	32,743	60,034	168,527	32,570	27,462	168,115
2012-13	1,920	61,092	96,469	41,653	127,223	18,122	55,143	240	10,234	11,516	8,395	64,194	19,538	48,428	118,452	24,136	20,285	131,804
2013-14	2,022	40,919	76,109	30,065	123,494	13,071	41,611	275	11,272	15,326	10,131	79,136	21,462	52,357	106,980	27,228	17,122	112,665
(b) Precipitation on off-channel water store (ML)																		
2010-11	4,629	161,898	232,621	135,758	166,545	33,357	100,744	643	19,186	25,183	10,075	97,124	40,877	69,849	138,482	33,674	34,155	120,551
2011-12	4,199	144,122	196,067	182,038	169,046	30,460	104,836	557	17,891	15,353	8,102	70,821	22,964	52,765	110,410	25,079	17,284	112,790
2012-13	2,096	118,996	122,910	103,647	92,062	19,094	65,435	232	7,025	9,707	6,149	42,637	14,888	35,633	67,293	16,614	13,521	64,433
2013-14	2,311	77,637	93,964	74,774	100,067	14,724	50,469	255	7,139	14,701	8,272	65,898	21,158	44,525	77,719	23,082	17,791	73,058
(c) Runoff harvesting into off-channel water store (ML)																		
2010-11	4,116	100,089	259,484	55,149	196,035	31,378	87,974	1,100	38,606	34,282	20,330	97,016	60,012	63,456	194,085	28,535	58,056	185,855
2011-12	4,117	100,793	190,293	98,936	185,387	32,283	89,669	1,188	40,303	20,774	13,493	79,334	34,351	50,453	158,636	23,748	32,553	164,636
2012-13	2,731	102,313	159,399	56,140	148,047	27,934	72,249	477	16,692	12,615	12,346	64,100	22,824	43,978	119,825	22,626	24,841	136,483
2013-14	3,388	64,356	125,864	44,832	162,160	20,740	57,895	663	20,999	20,296	16,605	82,840	29,374	50,944	119,423	26,404	27,747	129,041
(d) Evaporation from off-channel water storages (ML)																		
2010-11	6,059	173,401	250,701	146,289	212,119	41,360	115,589	1,074	29,794	23,494	13,366	84,781	40,824	62,588	153,873	21,973	42,797	152,535
2011-12	5,913	175,878	252,274	187,311	222,810	39,696	125,656	1,024	29,293	21,973	12,354	82,306	37,553	58,195	147,228	22,298	39,360	150,209
2012-13	3,582	145,398	189,219	122,974	166,650	29,635	92,727	607	18,908	17,355	10,859	74,056	29,245	51,612	125,968	22,597	28,748	127,663
2013-14	4,004	114,041	154,383	97,600	171,884	24,985	79,723	574	15,986	16,506	11,565	71,101	27,579	51,695	119,975	21,851	30,278	125,589
(e) Water use (ML)																		
2010-11	2,554	75,940	215,283	37,841	141,005	24,655	68,393	709	30,187	23,585	12,141	81,447	38,434	50,227	123,110	29,776	29,570	121,654
2011-12	2,085	68,639	150,254	75,981	121,223	22,601	61,952	659	28,040	18,069	8,665	70,878	28,235	44,978	111,748	27,283	23,369	108,945
2012-13	1,956	72,150	131,807	45,706	105,731	19,364	52,899	414	17,056	15,552	10,834	65,455	23,492	40,056	108,421	24,690	16,487	106,238
2013-14	1,585	49,607	85,706	33,572	94,021	15,474	42,127	307	11,092	14,636	11,618	62,648	20,988	39,897	88,579	24,557	18,365	95,601

Table 3. Results for the whole MDB

Reporting line item in NWA	2010-11	2011-12	2012-13	2013-14
Off-channel water storages	1,132	1,153	859	781
Precipitation on off-channel water store	1,425	1,285	802	768
Runoff harvesting into off-channel water store	1,516	1,321	1,046	1,004
Evaporation from off-channel water storages	1,573	1,611	1,258	1,139
Water use	1,107	974	858	710

There are about 210,350 farm dams in the northern and 379,820 in the southern part of the MDB. Despite the greater number of farm dams in the south, the north has greater total capacity which implies that on average the farm dams in the north are larger than those in the south. The rainfall over the MDB has decreased from 779 mm in 2010-11 to 388 mm in 2013-14 and this pattern in evident in the fluxes shown in the Table 2.

In summary, the application of the FDM in NWAs for the MDB region was quite efficient and required less run time (a few days compared to more than a week for STEDI) in terms of processing the inputs and outputs while dealing with large numbers of farm dams located within the MDB.

5. CONCLUSIONS AND FUTURE WORK

Due to the limitations in the STEDI model, a FDM was developed and successfully verified against the STEDI model. Subsequently, the FDM was applied to estimate the volume of water stored at the farm dams as part of the NWA for the MDB region. This model has been used to produce the farm dam related items for the National Water Accounts since 2012.

At present, the farm dam modeling has been performed independently to the operational AWRAMS and the impacts of their flow interception is overlooked most of the NWA region. However, it has shown that there is a significant impact of farm dams on catchment runoff within the MDB. Therefore, it is planned to incorporate the farm dam modeling into the AWRAMS in the near future. The integration of the FDM model with the operational AWRAMS will allow assessment of farm dam impact on catchment runoff which is an input to the AWRA-R. It will be a two stage processes. In the first stage, the runoff from the AWRA-L will be modified by running the FDM model. In the second stage, the modified runoff will be used as an input for the AWRA-R model unlike the current FDM approach where catchment runoff from AWRA-L is given as an input to AWRA-R without considering the farm dam impacts.

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