A Preliminary Dry-Season Water Balance for the Upper Laura River Catchment and Lakeland Agricultural Region, Cape York Peninsula:
Implications for Development and Downstream Impacts

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EXECUTIVE SUMMARY

A water balance for the upper Laura River catchment and Lakeland agricultural district was developed for the dry seasons of 2014 and 2015 using preliminary available data. A water balance, also known as a water budget, measures the flow of water in and out of a hydrological system over time. Water balance is an important tool for assessing water resource availability and sustainability. The water balance will help inform decision making on water resource development, expansion of agriculture, trade-offs between upstream and downstream users of water, and potential environmental and cultural impacts of water use. This preliminary study builds on past research and monitoring in the district and requires reassessment in the near future to improve the accuracy and detail as more local data become available.

This water balance model consists of two interconnected surface and groundwater control volumes, and includes three flux terms, namely, rainfall, streamflow, and evapotranspiration. It assumes that surface reservoirs are supplied with precipitation and surface runoff from tributaries. Water is extracted from reservoirs through evaporation, pumping, and surface outflow. The groundwater is augmented with percolation and depleted through evapotranspiration, pumping and baseflow. Monthly time series of weather and hydrological variables, spatial data on soils, stream channel network, and areas of surface water storages were collected and used to calculate monthly changes in surface water storage, groundwater storage, and downstream baseflow. Monthly domestic and industrial uses were also estimated. The water use requirements of bananas and other crops in the Lakeland district were estimated using well established methods for calculating crop evapotranspiration. Future development scenarios were analysed using the water balance under double (2x) and quadruple (4x) the current banana production to assess potential water and crop limitations.

The results calculated for Lakeland estimated that 12 to 14 ML of irrigation water are required per hectare per year for bananas, which is similar to local Lakeland farmer estimates for irrigation demand. For the current 465 hectares of banana cultivation, banana water use (evapotranspiration) was the largest consumer of water (5192 ML) over the 2014 dry season compared to other crop water use (2416 ML). Surface reservoir evaporation (4193 ML) from the relatively small reservoir area (231 ha) exceeded natural evapotranspiration (3556 ML) from soil, groundwater and vegetation combined across the entire catchment (548.6 km^2). In 2014, surface outflow from the catchment in rivers and creeks (4213 ML) was less than half (43%) that of direct anthropogenic uses including crop, industry and domestic uses (9723 ML); and only 30% of total anthropogenic uses if surface reservoir evaporation is included (13,916 ML). In the drier 2015, surface water outflow (602 ML) was 7.9% of direct anthropogenic uses including crop, industry, domestic uses (7633 ML), and only 5.1% of total anthropogenic uses if surface reservoir evaporation is included (11,826 ML). In the late-dry season months, stream baseflow volumes equated to 4% of the volumes of direct crop consumption in 2014 and 0.1% of direct crop consumption in 2015.

These preliminary water balance results for the dry-season of 2014 and 2015 indicate that limited water resources exist in the upper Laura River catchment and Lakeland Agricultural district. Under the current scenario (465 ha of bananas), there is a water deficit for banana irrigation during years with below average precipitation, with only minimal surplus during average years. If banana cultivation is doubled (800 ha) or quadrupled (1600 ha), then during an average year there would be a water deficit from Nov-Dec or Sept-Dec respectively. The

full drawdown of both groundwater storage and surface water storage would have severe impacts on 1) the integrity of the basalt aquifers, 2) the sustainability of agriculture in Lakeland, 3) downstream environmental flows, and 4) Groundwater Dependent Ecosystems.

Recommendations are provided for future field data collection in the upper Laura River catchment and Lakeland agricultural district to better quantify the full water resources and their multiple uses (agricultural, domestic, stock, environmental, cultural). Future research requirements to improve water balance calculations to a higher level of detail across the entire water year on a continuous basis are also provided. Detailed and integrated studies of environmental flow and agricultural water use will require a more thorough assessment using field-based observations, along with improved quantification of the water balance and reduced reliance on assumptions inherent in numerical modelling of water resource systems.

With groundwater already over-allocated or poorly managed for cooperative conjunctive use, many farmers are considering building new and bigger dams to capture wet-season floodwater as well as additional spring water baseflow during the dry season. However, the potential cumulative impacts of these proposed dams have largely been overlooked to date. For example, proposed dams on Ninda Creek and the West Normanby River would significantly increase the cumulative dammed area of the upper Laura-Normanby catchment. They would require considerable capital and pumping costs to store and pipe water into Lakeland, potentially making them economically unviable. Damming Ninda Creek would truncate important Groundwater Dependent Ecosystems (GDEs) and reduce environmental baseflows further downstream in the Laura River. Damming the large West Normanby River, similar to other large size dams in northern Australia (e.g., the Ord River), would impact the health and productivity of riverine, aquatic and estuarine ecosystems downstream, as well as cultural values and usages of water, and integrity of the iconic Rinyirru (Lakefield) National Park and Princess Charlotte Bay.

Reduced water flow and increased pollution as a result of new dams and expanded agricultural chemical use could have significant impacts downstream in the Laura-Normanby catchment. Decreased water flow, especially reduce baseflow during dry seasons, would impact downstream water users including: Aboriginal people who utilise the Laura River for subsistence living; the Laura community and township; stock water; domestic surface and groundwater supplies; springs that feed Groundwater Dependent Ecosystems; river riparian ecosystems; and migratory fish and habitat use. Increased irrigated agriculture will increase the application and release of fertilisers, herbicides and pesticides, which could elevate pollution downstream in the Laura River and further degrade existing water quality draining into the Great Barrier Reef Lagoon.

This study raises concerns about the impacts upstream water use may have on downstream values and functions if the current agricultural expansion continues without adequate planning and management for sustainability of economic, environmental, and cultural resources. It is recommended that any new dams and irrigated agriculture expansion have full environmental impact assessments conducted before project implementation, along with 'no action' alternatives. This will be essential to determine local, direct and indirect impacts, and the cumulative effects of damming multiple springs, creeks and rivers in the Laura-Normanby catchment. A full cost-benefit analysis of the economic and social trade-offs between various values of water should also be included in any assessment, such as agricultural, domestic, stock, environmental, other commercial (fisheries, tourism), and cultural uses and values of water.

The report ends in a discussion of the potential for innovative water management and use efficiency through 1) increasing crop water efficiency and adjusting the types of crops grown, 2) reducing reservoir evaporation through technological advances, 3) utilising ‘conjunctive use’ between surface water and groundwater resources through ‘Aquifer Storage and Recovery’ (ASR), and 4) floodwater harvesting in the wet season by pumping flood water into off-stream storage reservoirs and/or basalt aquifers. These alternatives could be cost effective compared to the higher costs of dam construction, reservoir piping and pumping over large elevation heads, reservoir siltation, and externalised environmental and economic value impacts of building new large dams. These management tools could help ensure sustainable water supplies for future agricultural as well as maintaining downstream values, and can create ‘win-win’ situations.

Increasing crop water use efficiency or crop variety could conserve more water for additional crop area and/or environmental flow maintenance. The banana plant is a heavy consumer of water. New irrigation technology, improved irrigation scheduling avoiding daytime irrigation, and more effective delivery networks could reduce water usage. Alternative high value crops, that use less water per hectare than bananas, are worth ongoing investigation for an improved mix of agricultural production. These include watermelon, passionfruit, and papayas, or other non-fruit crops with high value returns. The equitable use of and access to water between both small and large producers, of a variety of crop types, and downstream users (cultural, environment), will be important to negotiate through the upcoming Water Resource Plan process.

In Lakeland, water evaporation from artificial surface storage (4193 ML) is enough water to irrigate another 350 ha of bananas, or 1400 ha of watermelon. Technology to reduce reservoir evaporation is improving, and includes 1) monolayer chemical films that are benign and wind resistant for months to a year, and 2) polyethylene ‘shade balls’ that can reduce evaporation by up to 85%, are wind resistant when partially filled with water, and are constructed to environmentally safe drinking water standards. These technologies may be suitable and cost-effective for small to medium sized reservoirs in Lakeland.

The harvest of floodwater via pumping water in the wet season into off-stream storage reservoirs (aka ‘Water Harvesting’) can be a sustainable alternative to damming rivers and creeks across their main channels with resultant major environmental impacts. Floodwater pumped from deep pools on stable stream banks could be diverted into 1) existing dams as a top-up, 2) into new off-stream storage reservoirs on ephemeral tributaries or valley depressions, and/or 3) basalt ground water aquifers used for ‘Aquifer Storage and Recovery’ (ASR). Water pumping rules could be instated to dictate the streamflow discharge thresholds above which water could be pumped during floods, months of diversion (Jan-Mar), as well as total volume of diverted water. Several water licenses already exist for run-of-the river floodwater harvesting in the wet season in the upper Laura-Normanby catchment.

‘Conjunctive use’ between surface water and groundwater resources normally involves ‘Aquifer Storage and Recovery’ (ASR), by actively storing surplus surface water in groundwater aquifers or basins in wet years and wet seasons, and withdrawing this water from aquifers and reservoirs during dry periods. ASR in the McClean Basalt at Lakeland could occur in 3-4 separate aquifer management units, but would require significant cooperation between water users, and involve monitoring, research, and adaptive management. ASR at Lakeland could be a cost effective and efficient management tool to ensure sustainable water supplies for agricultural, as well as ensure there is enough water to maintain downstream environmental flows in springs, creeks and rivers of Groundwater Dependent Ecosystems.

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1 INTRODUCTION

1.1 Background

Considerable interest has been expressed towards increasing land and water resource development (e.g. irrigated agriculture, inter-basin water transfers, intensive grazing) in the tropical savanna landscapes of northern Australia (e.g. Davidson 1965; Woinarski and Dawson 1997; Camkin et al., 2007; The Australian Government 2015). This interest has continued despite identified economic and technical challenges, geographic remoteness, and environmental impacts (e.g. Davidson 1965, 1969; Bauer 1978; Basinski et al. 1985; Woinarski and Dawson 1997; The Australian Government 2015). These challenges are a partial result of the significant limitations imposed by northern Australia's natural climate, hydrology, geomorphology, soils, and location of the region (e.g. Davidson 1965, 1969; Smith et al. 1983; Petheram et al. 2008; CSIRO 2009, 2010). Many agricultural development successes have been made in Northern Australia; however, these stand by many failures and impacts.

Water and agricultural development often involves trade-offs between upstream users (farmers, graziers, miners) and downstream users (other farmers, Aboriginal people, aquatic ecosystems, fisherman, urban areas). "*Contrary to popular belief, water resources in the north are neither unlimited, nor wasted*" (CSIRO 2010). Aboriginal people's rights and interests to water and land in northern Australia are often overlooked and not considered when developing equitable and sustainable uses (Ross 2009). Under current development paradigms, "*Indigenous people not only have more to lose from 'development' which erodes natural capital than do non-Indigenous people, but they also have significantly less to gain*" (Stoeckl et al. 2013). Downstream Aboriginal water right holders and users have generally not been involved in upstream development plans. The ecosystem services provided by downstream freshwater flows are also not well quantified or considered in development planning, leading to inadvertent impacts on subsistence and commercial fisheries in rivers, waterholes, estuaries, and off-shore marine waters (Burford et al. 2010; Waltham et al. 2014).

The Lakeland agricultural district in the upper Laura River catchment (greater Normanby catchment) in north-eastern Australia is used here as a case study area. The district is an example of a modestly successful agricultural industry since the 1960's. This is largely due to the small pocket of rich basalt soils covering 10,000 ha and the associated underground aquifers and sub-artesian springs. This area has been largely cleared of native vegetation, dams and bores have been installed, and a variety of crops have been grown, both successfully and unsuccessfully in terms of economic and environmental sustainability. There are current plans to expand water and agricultural development in the district, despite known limitations in water availability (QDNRM 2013a; 2013b). Recent commercial banana production has been stated as an economic success, and is proposed for expansion. However, its market success as an 'insurance crop' depends on supply limitations from natural disasters in coastal banana growing regions. Significant economic losses can occur during times when prices are lower than break-even costs and many bananas go to waste (e.g., 2016).

As a consequence of agricultural expansion, and associated fertiliser use, downstream impacts on water quality from elevated nutrients (e.g. dissolved nitrogen) have been documented in the Lakeland district (Howley 2010; Howley and Moss 2015). This has raised concerns over increased pollution of the relatively pristine northern Great Barrier Reef, which the Laura and Normanby Rivers flow into (Howley et al. 2013). Damming springs and creeks directly, in addition to cumulative pumping from groundwater bores, has reduced downstream dry season baseflows and water volume (examples in this report), but these changes have been poorly quantified in many cases. Changes in baseflow and stream connectivity from dams have impacted sub-artesian springs, Groundwater Dependent Ecosystems (GDEs) (most that are not officially mapped), and migratory aquatic species. Nutrient pollutants from agriculture have also been concentrated in smaller volumes of water downstream of dams, thus exacerbating riverine algal blooms (Howley 2010; Howley et al. 2013; Howley and Moss 2015).

The objectives of this report are to develop a preliminary dry-season water balance for the upper Laura River and Lakeland district to determine if there is enough water available during the dry season to support additional agricultural enterprises; help inform decision making on development and scenario trade-offs, and better understand potential downstream impacts of development. This water balance model relies on past research conducted in the area (QDNRM 2013b); but will need to be built upon in the near future to improve its accuracy and detail as more local data become available. Previous regional water balance modelling has largely omitted and missed the hydrological details and impacts of this district (CSIRO 2009).

1.2 Specific Objectives

The primary objectives of this report are to:

1. Estimate the water use requirements of bananas in the Lakeland district using established methods for calculating crop evapotranspiration.
2. Develop a preliminary dry-season water balance from a variety of available data sources for the upper Laura catchment that encompasses the Lakeland district.
3. Analyse future scenarios for banana water use and potential water limitations using the preliminary water balance.

The secondary objectives of this report are to:

4. Provide recommendations for future field data collection to better quantify the full range of water resources and multiple uses (agricultural, domestic, stock, environmental, cultural) in the Lakeland district, as well as improve water balance calculations at a higher level of detail across the entire water year.
5. Discuss the potential impacts of water resource development on downstream water users (environmental, cultural, domestic, stock, fisheries, tourism).
6. Discuss the potential for innovative water management and use efficiency through a) crop water efficiency and type, b) reducing reservoir evaporation through technological advances, c) 'conjunctive use' between surface water and groundwater resources, and d) floodwater harvesting in the wet season into off-stream storage reservoirs and/or basalt aquifers.

1.3 Study Area in the Upper Laura River Catchment

The upper Laura River catchment is located in the greater Normanby River catchment that drains into Princess Charlotte Bay and the Great Barrier Reef Lagoon in Cape York Peninsula, North Queensland (Figure 1 inset). The Lakeland agricultural district is located in the headwaters of the Laura River catchment (Figure 1). The area has a wet-dry tropical savanna climate with an average rainfall of 923 mm per year occurring predominately between December and April. Elevations range from 140 m to 500 m, with Lakeland located at 260 m. The catchment geology is variable between the Hodgkinson Formation (metamorphic greywacke, siltstone, mudstone) and the McClean Basalt (basalt lava flows). Soil types vary according to this geology and their elevation along soil catenas and basalt flows. The area is drained by the Laura River and several major tributaries (Bullhead, Spring and Ninda Creeks), as well as Boggy Creek and Leichhardt Creek that drain into the West Normanby River.

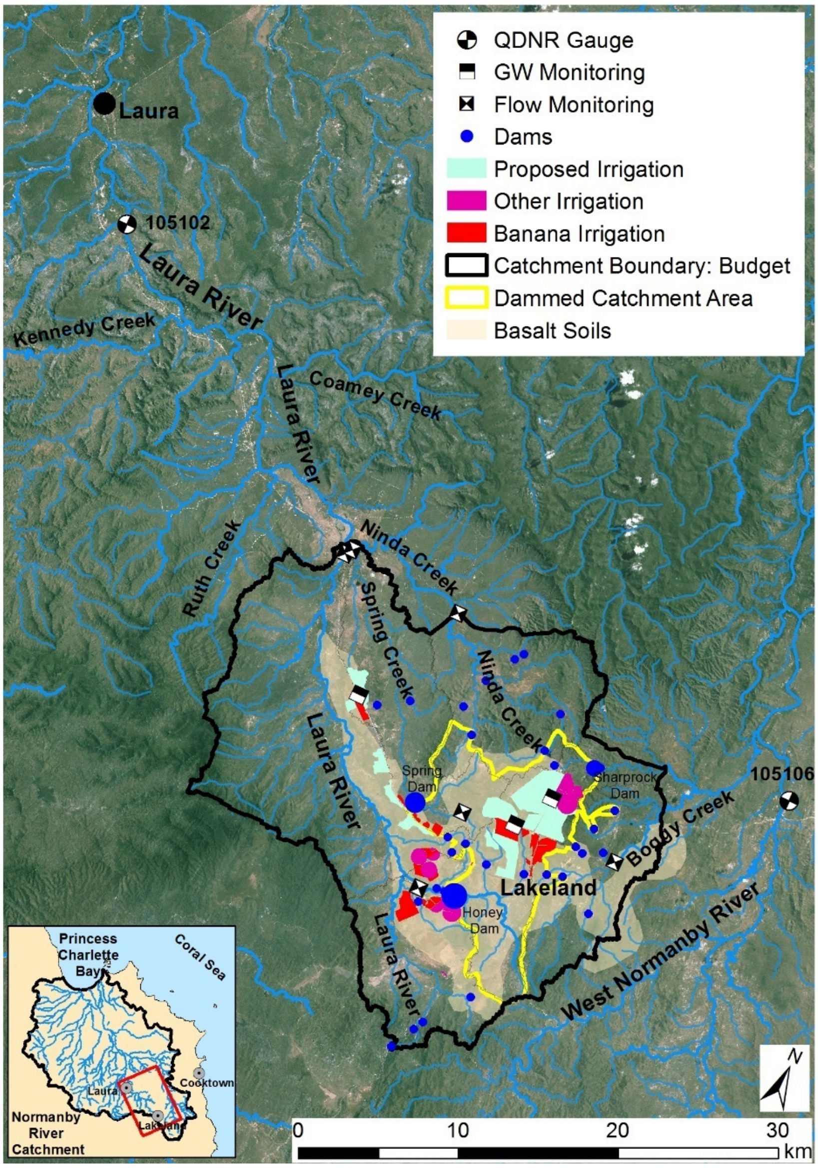

Figure 1 Map of the upper Laura River catchment and Lakeland agricultural district, showing the area of current banana production, other irrigated crops, proposed development, existing dams, and monitoring locations. Inset map shows the study area in red in the upper Normanby catchment.

1.4 Lakeland Agricultural District

The Lakeland agricultural district was developed and divided in the 1960's from the previous Butcher's Hill cattle station (Wallace 2012). Lakeland was named after the early European settler and prospector William Lakeland. Since the 1960's, >8,000 ha of native savannah woodland have been cleared for agriculture, with ~ 5,000 ha being actively maintained for grazing and to a smaller extent agricultural crop production. Agriculture is concentrated on basalt soils of the McLean Basalt which cover ~10,000 ha (Grundy and Heiner 1994; QDNRM 2013b) (Figure 1).

Lakeland is a small farming town and district with approximately 227 people. Historically a variety of crops were grown at Lakeland, including, peanuts, maize, sorghum, coffee, tea and tropical fruits, in additional to cattle grazing. Today, production has shifted to bananas, tropical fruits, watermelon, chia, beans, sorghum, cattle hay, teak plantations, and general grazing. Bananas have become a major focus of development, with several corporate agricultural companies buying and developing land in recent years as a potential way to offset banana losses associated with natural disasters along coastal production areas.

Both local and regional economic interests hope to expand agricultural and water development in the Lakeland district into the future. Local residents are well aware that future development depends on the availability of water, but also that more knowledge of water resources is needed to ensure the sustainability of development, maintain environmental water flows, and minimise local and downstream impacts.

1.5 Aboriginal People in the Laura Catchment

About 60 km downstream of Lakeland is the town of Laura located on the banks of the Laura River (Figure 1). Laura has a population of 225 people, most of whom are Aboriginal people of multiple clan and language groups from country in the surrounding region. The area includes the internationally recognised Quinkan Aboriginal Rock Art and the Laura Aboriginal Dance Festival. Cultural tours are conducted through the sandstone country at Laura River corridor. The Laura Aboriginal Dance Festival is held bi-annually on the banks of the Laura River, with associated swimming and fishing. Aboriginal people in the Laura catchment are culturally, spiritually, socially, and economically connected to their local river systems, fishing, hunting and connecting with country on a regular basis. They are dependent on the health of river systems for their cultural maintenance, social well-being and subsistence living. They have inherent rights and values to water and associated ecosystem health and functions on their traditional country.

Many Aboriginal people in the Laura catchment are concerned about the impacts of upstream agricultural development on water flow and volume downstream in the Laura River, specifically during the dry season. Water quality, nutrient and sediment pollution of waterholes are also of concern. Local Council limitations on drinking water and domestic water use and associated costs in Laura are a major concern. In contrast, water resource development and consumptive use is being actively encouraged upstream at Lakeland. Locals have noticed over the last 50-years that permanent water holes along the Laura River have been drying up more rapidly in the dry season, potentially due to 1) climate variability, 2) agriculture water extraction upstream, and 3) sedimentation of river pools by silt and sand from accelerated erosion generated by historic land use change (grazing and agriculture) (Brooks et al. 2013).

1.6 Water Resource Development in the Laura Catchment

Water resource development for irrigation in the upper Laura River catchment has focused on damming creeks and sub-artesian springs to impound water in reservoirs, and drilling groundwater bores (wells) into the aquifers of the McLean Basalt. More than 18 dams have been constructed within the basalt area of Lakeland, which cumulatively capture 99.1 km^2 of the upper Laura River catchment area (Figure 1). Additional smaller farm dams exist outside the basalt area. Many of the dams built in the 1960's and 1970's were unauthorised when built. Additional dams are actively being built through reduced regulation and generalised permitting, which are a policy result of recent drought conditions and limitations of ground water available for irrigation (QDRNM 2013a; 2013b).

The current dammed catchment area (99.1 km^2) represents 18.1% of the study area (548.6 km^2) of the Laura River catchment upstream of the Carroll's Crossing bridge and a very small part of the West Normanby catchment draining Lakeland to the east. The cumulative dammed area is 7.5% of the area (1326 km^2) upstream of the Laura River stream gauge (Coalseam 105102), and the town of Laura. Historically, a dam (Broken Dam) was also built directly across the Laura River main channel downstream of Lakeland, capturing more of the catchment area. However, this dam failed before its final completion.

There are hundreds of freshwater springs draining the McLean Basalt and sub-artesian aquifers in Lakeland. Many of the largest springs have been targeted for dam building to capture perennially flowing spring water, with dams placed either downstream or on top of springs flowing out of the basalt. These dams therefore capture both surface water runoff during the wet season (Jan-March) and perennial spring water during the dry season, therefore maximizing retention of water from the McLean Basalt. Irrigation pumps are present at the largest and most important dams to withdraw water. Many pumps have inbuilt flow meters, but are not monitored by the State of Queensland to quantify use or regulate allocation of water rights.

Flow release gates or pipes are not-present on most earthen dams, with flood water released from by-wash spillways. The dams have a State legal requirement to release water flows to downstream reaches; "*When there is a flow in the watercourse into the storage sufficient downstream flow must be maintained to meet downstream requirements*" (QDNRM 2013a). The "*downstream requirements*" are not quantified, but are assumed to equal upstream natural baseflow inputs from springs and groundwater seepage, as well as to meet the requirements of other water users downstream and environmental flows for Groundwater Dependent Ecosystems (GDEs) of springs and creeks. However, in practice most dams do not have active or functional release facilities to meet these downstream requirements, especially during dry season (May-December) baseflows, nor are monitoring and enforcement measures in place. However, some dams such as Honey Dam, the largest in the district, leak water through the dam wall in an uncontrolled fashion and provide some environmental flow downstream, but leakage has been targeted for reduction in recent years through dam modifications and sealing. Only Honey Dam has written instream flow requirements for downstream releases, ranging from 2-10 L/s depending on water storage. In practice this is met through unregulated seepage that varies with storage.

There are > 78 groundwater bores documented bores in the Lakeland district, a majority of which have been drilled into the McLean Basalt aquifers since the 1980s (QDNRM 2013b; QDRNM 2014). Most have not been monitored or regulated to understand water use rates for agricultural, stock, and domestic uses. Other unregistered (or illegal) bores may also exist. In 2014, irrigation and town bores in the main basalt aquifer near the centre of Lakeland were required to be monitored (QDNRM 2013b; QDRNM 2014), but not more distant bores. In 2010, the State installed 5 monitoring bores in the district to track changes in groundwater levels and responses over time to the cumulative impact of agricultural pumping from the aquifers. The State recently (2013) put a moratorium on groundwater withdrawals from much but not all of the McLean Basalt aquifers, citing over-allocation and over-draft following a detailed review and estimation of the storage volume of the aquifers and their sustainable yield (QDNRM 2013c).

Following the moratorium on groundwater withdrawals (2013), the previous State government deregulated all water impoundments and withdrawals from headwater spring catchments < 20 km^2 (QDNRM 2013a). In this special Lakeland situation, all water in catchments < 20 km^2 were re-defined as "*overland flow*" not in a "*watercourse*", essentially legislatively ignoring many hundreds of real water channels, creeks, springs, GDE's or wetlands. This regulation left water right negotiations up to adjacent landowners to work out together, left unclear the volume requirements to release water downstream of new or existing dams for environmental flow and other water users, omitted the environmental impact assessment of damming watercourses, and ignored the potential of additional cumulative impacts from multiple dams.

Most recently in 2016, the State has placed a partial moratorium on water resource development for several years until a new statutory Water Resource Plan for all of Cape York is developed (QDNRM 2016). This applies to both legislatively defined surface watercourses and groundwater not connected to the Great Artesian Basin (i.e., sub-artesian aquifers and springs). Apparently it does not apply to catchments < 20 km^2 in Lakeland that have been legislatively defined as "*overland flow*" not in a "*watercourse*" in 2013 (QDNRM 2013a). Therefore, proposed dams in these 20 km^2 catchments have continued to be built in recent times. A range of technical assessments on environmental, hydrologic, cultural, and socio-economic topics are planned to "*support future economic development opportunities for the people of Cape York and protect the unique environmental values of the Cape*" (QDNRM 2016).

At the same time, additional proposals for large dams in the Lakeland area continue to be put forward by regional groups, with recent funding for a dam feasibility study on the West Normanby River in the hopes of future government dam subsidies (FNQROO 2016). Proposals for additional moderate sized dams in Lakeland also continue, which if all are constructed, could double the cumulative dam catchment area and impact in the next 10 years (QDNRM 2013a).

1.7 Quantifying Upstream Uses and Downstream Water Flow in the Upper Laura Catchment

A water budget or water balance is needed to quantify the available water resources of the upper Laura catchment in terms of surface water and groundwater. However, the lack of water use monitoring data for agriculture in the Lakeland district makes quantifying a water budget or water balance difficult, as does limited local hydrological data. Therefore, for use in this report, the evapotranspiration water requirements for crops, specifically bananas, are calculated using local and regional weather and climate data and used to estimate agricultural water demand and use. Estimates of catchment evapotranspiration and reservoir evaporation are also made, and compared to rainfall inputs. These data are compared to available estimates of both surface water storage (QDNRM 2013a) and groundwater storage (QDNRM 2013b).

The historic lack of streamflow information in springs and creeks of the upper Laura catchment has been partially overcome by recent local monitoring improvements. These preliminary data are used here to estimate streamflow output from the catchment during dry-season baseflow. However, the lack of streamflow data during peak flow (floods) in the wet season limits the ability to calculate water balances over the entire water year. Therefore, this study focuses on calculating water balances during the dry-season of two different years with contrasting wet-season rainfall inputs. This preliminary analysis will be useful toward building full water budgets of inputs, storage, and outputs from the upper Laura catchment.

2 METHODS

2.1 Banana Water Use Estimates for the Lakeland Area

2.1.1 Introduction

In recent years the area under banana production in the Lakeland area of the upper Laura River catchment has increased to approximately 465 ha as measured from satellite images in 2015. This area is expected to increase further in the coming years as demand for development continues. Some have projected that banana cultivation could double (800 ha) or quadruple (1600 ha) in the coming decades across the >5,000 ha of actively maintained cleared land on basalt soils at Lakeland. However, the success of these projects is largely dependent on water use and availability.

Figure 2 Banana cultivation at Lakeland.

2.1.2 Banana Water Use Methods

Due to its large leaf area and vigorous growth, the banana plant is a heavy consumer of water. Water deficits badly affect crop growth and yields:

1. During the early vegetative period, an adequate water supply is essential in determining the potential for growth and fruiting.
2. During the vegetative and flowering period, water deficits limit leaf growth, which in turn influences the number of flowers and fruits produced.
3. During yield formation, water deficits can cause late flowering, which affects fruit size and quality. A reduced leaf area influences the rate of fruit filling and small fruit are older than they appear at harvest time.

Banana plants are grown in a wide range of climatic conditions with varying precipitation and evapotranspiration rates. In some areas, rainfall can fulfil all the crop requirements, while in dry areas irrigation is needed. In the Lakeland region located in a wet/dry Tropical Savannah climate, the banana fields require regular irrigation throughout most of the year.

Figure 3 Irrigation of young banana plants during the dry season in Lakeland.

Precipitation is not evenly distributed across the year in Lakeland and the Laura catchment, with > 85% of the average annual rainfall (923 mm) occurring in the summer between December and April inclusive (BOM 2015 climate data). High water consumption by bananas is concurrent with low precipitation months in the dry season May-November. Irrigation of bananas is essential during the dry season in Lakeland.

The prevalent irrigation system for banana fields in the study area is under-canopy sprinkler irrigation with typical rates between 30-50 L/hour depending on exact sprinkler type, water source, and irrigation method. The exact irrigation efficiency is unknown, but could range from 70% for conventional sprinklers to 85% with the use of micro sprinklers and targeted irrigation according to weather and wind conditions, and time of day (early morning preferred). Drip irrigation is generally not used in the area, but new technology such as field soil moisture and electrical conductivity metres are increasingly being used to guide water application on a rotating basis through plantations throughout the day.

Regular water supply to bananas under irrigation over the total growing season, as compared to rain-fed production with seasonal differences in water supply, produces taller plants, with greater leaf area, and results in earlier flower shooting and higher yields. Interval between irrigation has a pronounced effect on yields, with higher yields being achieved when intervals are kept short. Under conditions of limited water supply, total production will be higher when full crop water requirements are met over a limited farmed area, than when crop water requirements are partially met over an extended farm area.

The FAO Penman-Monteith method for calculating crop evapotranspiration (Allen 1998) was used to estimate the amount of irrigation water required to fulfil the water demand for banana production at Lakeland. Both the current status as well as future development scenarios were analysed. As a result of an Expert Consultation held in May 1990, the FAO Penman-Monteith method is now recommended as the sole standard method for the definition and computation of the reference evapotranspiration. The FAO Penman-Monteith method requires data on solar radiation, air temperature, air humidity and wind speed from local sources or gridded regional estimates.

The Penman-Monteith method initially calculates the evapotranspiration from the reference surface (ETo) based on climate data. The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec/m and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground.

The climate information need to calculate ETo are monthly average minimum and average maximum temperatures, relative humidity, wind speed, and sunshine. Bureau of Meteorology (BOM) weather data from both Palmerville (85 km east) and Cooktown (57 km NE) stations were averaged to estimate monthly average temperature and humidity for use in the Lakeland project area, due to lack of local weather data. Monthly average wind speed data from Palmerville were used, as the average wind speed of Cooktown and Palmerville overestimated reference evapotranspiration beyond reasonable levels due to the strong wind gradients away from the coast. These data can be replaced and updated in the near future as more local weather data are collected directly at Lakeland. Sunshine hours data for Lakeland were estimated from BOM gridded climatological data of mean monthly sunshine hours data from 90 stations across the country and the closest sunshine hours station at Cairns (BOM 2015). The calculated monthly Reference Evapotranspiration (ETo) data for the Lakeland region are shown in Table 1.

Table 1 Estimated monthly Reference Evapotranspiration (ETo) for the Lakeland region.

Month	Min Temp °C	Max Temp °C	Humidity %	Wind Km/day	Sun Hours Range at Lakeland (Cairns Data)	Radiation MJ/m^2/day	ETo mm/day
January	23.6	32.4	71	134	6-7 (6.8)	21.1	4.99
February	23.5	31.9	75	117	5-6 (6.1)	19.7	4.53
March	22.9	31.3	72	113	6-7 (6.4)	19.1	4.35
April	21.4	30.7	67	116	6-7 (6.7)	17.6	4.03
May	19.5	29.4	66	114	6-7 (6.7)	15.7	3.47
June	17.5	28.1	65	114	7-8 (7.3)	15.3	3.19
July	16.6	27.8	63	135	7-8 (7.4)	15.9	3.39
August	17.1	28.9	59	149	7-8 (8.0)	18.5	4.09
September	18.9	30.7	55	161	8-9 (8.7)	21.7	5.06
October	20.9	32.4	55	182	8-9 (8.8)	23.4	5.85
November	22.6	33.4	57	178	8-9 (8.5)	23.6	6.04
December	23.5	33.4	63	153	7-8 (7.8)	22.6	5.63
Average	**20.6**	**30.8**	**64**	**139**	**7-8 (7.4)**	**19.5**	**4.55**

The development of the banana plant can be divided into three phases: vegetative, flowering and yield formation. The time from initial planting to flower shooting (vegetative phase) is about 7 to 9 months in the tropics, or longer in lower temperature climates. The time from flower shooting to harvest (flowering and yield phases) is about 90 days. After harvest, the plant can be multiplied vegetatively for the next cycle of production by selecting a new sucker (ratoon or follower) from the corm and cutting back others. Several types of suckers can be used for production. The number of ratoons varies. The average life of a commercial plantation can be from 3 to 20 years. Some varieties are replanted after each harvest. In Lakeland, banana plantations are continuous for up to 10 years or more with new ratoons selected after each fruit harvest. Therefore, the calculations for estimating the irrigation water requirement was carried out for ratoon cropping. Harvesting can happen year round depending on the growth cycle and ratoon development. For monthly budget and plant growth calculations in Lakeland, it was assumed that the harvest occurred year round rather than synchronous during one or two months.

Being a long duration crop, the total water requirements of banana plants are high. Water requirements per year vary between 1200 mm in the humid tropics to 2200 in the dry tropics. For rain-fed production, average rainfall of 2000 to 2500 mm per year, well-distributed, is desirable, but banana often grows under less rainfall. In relation to reference evapotranspiration (ETo), the maximum water requirements (ETm) can be determined with the crop coefficient (Kc), or ETm = Kc x ETo. The crop coefficient (Kc) incorporates crop characteristics and averaged effects of evaporation from the soil.

FAO has published monthly Kc values for Subtropical climates and banana ratoons starting from February (FAO 2015). As Lakeland has a wet-dry Tropical Savannah climate and ratoons are budgeted to start in July on average, the FAO monthly Kc values were modified and are shown in Table 3. The FAO Kc values were increased by 10% to adjust the values appropriately for the hotter and drier Tropical Savannah climate of Lakeland, rather than a Subtropical climate.

In order to calculate the net irrigation demand per hectare, the effective rainfall was deducted from the crop water requirement. The effective rainfall is that part of total rainfall that can be used by the plant from stored water in the root zone. The remaining portions of rainfall are either lost to deep percolation water, or water run-off from the soil surface both of which cannot be used by the plants. Average monthly rainfall data from Butcher Hill (031009) as representative of the Lakeland area. The USDA SCS method (Dastane 1978) was used to estimate the average effective rainfall for each month (Table 2).

Table 2 Average monthly rainfall and effective rainfall at Butcher Hill (031009) in Lakeland.

Month	Rainfall (mm)	Effective Rainfall (mm)
January	230.7	145.5
February	247.5	149.5
March	177.2	127.0
April	35.5	33.5
May	9.4	9.3
June	9.3	9.2
July	3.4	3.4
August	2.4	2.4
September	2.9	2.9
October	16.5	16.1
November	59.4	53.8
December	147.1	112.5
Total	**941.5**	**665.1**

2.2 Dry Season Water Balance

2.2.1 Water Balance Methods

A dry season (April-December) water balance was constructed for the upper Laura catchment using provisional available data for the 2014 and 2015 dry seasons. The water year 2014 was a relatively wet year, while 2015 was relatively dry, providing contrasting conditions for assessment. Modifications with additional data, seasons and years can be made in the future as more data become available. The wet season (Jan-March) was not included in this iteration of the water balance, as peak streamflow during flood periods are not available for the upper Laura River and its tributaries. This should be a priority for future empirical measurements at gauge stations.

A water balance algorithm was calculated in Matlab and Excel using the following water balance equation at the monthly time interval:

$\Delta Sg = P - ET - Q - \Delta S_S$

where ΔSg is the change in groundwater storage, P is the monthly precipitation, ET monthly evapotranspiration, Q monthly surface streamflow, and ΔS_S is the change in surface storage mostly in dams. The change in groundwater storage was estimated using the following equation:

$\Delta Sg = \alpha(Q)+W$

where W is the average monthly pumping from the groundwater based on estimated demand, and Q monthly surface streamflow outflow from groundwater, and α is baseflow recession coefficient.

The water balance model consists of two interconnected surface and groundwater control volumes, and includes three flux terms, namely, rainfall, streamflow, and evapotranspiration. It is assumed that surface reservoirs are supplied with precipitation and surface runoff from tributaries while water is extracted from them through evaporation, pumping, and surface outflow. The groundwater is augmented with percolation and depleted through evapotranspiration, pumping and baseflow.

Weather and hydrological variables were calculated and analysed at monthly time steps. Spatial data on soils, the stream channel network, and areas of surface water storages were collected and used to calculate monthly changes in surface water storage, groundwater storage, and downstream baseflow.

2.2.2 Data Inputs and Assumptions

- The total catchment area used for the water balance is 548.6 km^2, which encompasses the upper Laura River catchment above the Carrolls Crossing bridge and a very small part of the West Normanby catchment draining Lakeland to the east (Figure 1).
- The banana irrigation water requirement was estimated using the FAO Penman-Monteith method tailored to local conditions (see Section 2.1.2).
- Other crop irrigation requirements for local conditions (area planted by crop and water usage) were not readily available for this report. It was estimated that their average irrigation water requirement was one third (1/3) of the banana's in every month, which

is a conservative estimate. As more crop information becomes available in the future, this assumption will be corrected and applied to each crop.

- The area of banana plantations (465 ha) as well as other irrigable crops (649 ha) were delineated using detailed satellite imagery updated into 2014 and 2015.
- The average area of surface water reservoirs was delineated using satellite imagery for 2014 and 2015. In 2014 the area of surface reservoirs was estimated as 231 ha.
- Surface water storage volume in reservoirs was estimated using data from DNRM's Lakeland Surface Water Report (QDNRM 2013a) and dam construction database. The available surface water storage in the area was estimated at 13,249 ML with Honey Dam (6075 ML), Sharprock Dam (3300 ML) and Spring Creek Dam (1415 ML) representing the bulk of the volume at full storage. The availability of this water for crop irrigation is likely overestimated, as many small dams are not used for crop irrigation and the full reservoir volume is not all available for extraction. More precise measurements of actual and effective storage volumes also are needed.
- For the wetter 2014 water year, it was assumed the surface and groundwater reservoirs were full at the end wet season (April 2014). They were assumed to be 70% full at the end of the drier 2015 wet season (April 2015).
- Groundwater storage volume in basalt aquifers was estimated using data from DNRM's Lakeland Groundwater Review (QDNRM 2013b). The combined available storage was estimated as 7,250 ML, but likely does not include all groundwater in the total catchment.
- The area of basalt aquifer was estimated using data from DNRM's Lakeland Groundwater Review (QDNRM 2013b), which was estimated at 10,100 ha (Figure 1).
- The evapotranspiration from the groundwater was assumed to be 7% of the actual evapotranspiration (Evans 2007).
- Drawdown of surface water and groundwater storage volumes from irrigation pumping was assumed to be supplied 70% from dams and 30% from groundwater. These assumptions will need to be updated in the future with improved data.
- Bureau of Meteorology (BOM) empirical data and regional gridded information were used for temperature, humidity, wind, and sunshine estimations, as well as potential and actual evapotranspiration across the catchment area.
- Rainfall inputs were measured at a local QDNRM gauge for 2014 and 2015 (RN10510001) (Figure 1).
- Effective precipitation was estimated using the USDA SCS method (Dastane 1978).
- The streamflow outputs were estimated from existing data (2012-2015) available from several continuous baseflow gauges (Laura River at Carrolls Crossing, Ninda Creek below forks, Spring Creek above the Laura River), plus baseflow recession measurements at Boggy Creek and data from the Lakeland Groundwater Review (QDNRM 2013b) (Figure 1).
- Only gross inputs, storage, water use, and outputs were estimated, due to the complexity of the hydrology and springs in the catchment and district. Internal dynamics such as spring water emergence from the aquifers and recapture by dams,

and agricultural return flow, were not accounted for. The model complexity can be refined in the future with additional data internal to the greater catchment area.

- The population of the Lakeland area (227 people) was determined from the Australian Bureau of Statistics for the estimation of domestic water consumption at an average rate of 200 L/day per person.
- Stockwater use was not included in this model iteration, but should be incorporated in the future.
- The banana yield per ha and banana packing water consumption (industrial) were estimated using variety of local, provincial, national and international documents (Sikirica 2011; Dole 2011). Banana yield was estimated at 27 tonnes/ha, but could be as high as 50 tonnes/ha due to high nutrient and water application rates. Packing water usage was estimated at 0.0038 ML/tonne (3800L/tonne). This industrial consumption was spread through the year during variable harvest periods. More local data are needed to refine industrial consumption rates.

2.2.3 Scenarios

The model was run for the following three scenarios:

1) Current cropping conditions with 465 ha of bananas and 649 ha of other crops

2) Future conditions with double (2x) and quadruple (4x) banana cultivation

3) Past conditions with no water extraction and surface reservoir storage, assuming that discharge from the groundwater is the same as the baseflow in streams.

3 RESULTS

3.1.1 Banana Water Use Results

The calculated monthly irrigation water requirement for bananas at Lakeland is shown in Table 3. These data indicate that of the 1639 mm per year of water needed to support a banana crop in Lakeland, only 665 mm are fulfilled from effective precipitation. The remaining 977 mm requires irrigation, concentrated in the dry season April to December. These data were converted to megalitres (ML) per hectare (ha) (ML/ha) to scale up these data to the area of current (400 ha) and potential future (1600ha) banana cultivation in the Lakeland region and upper Laura catchment (Table 4). Two estimates were provided, one assuming the use of conventional sprinkler irrigation with an efficiency of 70%, and the other with the use of micro irrigation systems with an efficiency of 85%. From these data, it is estimated that 12 to 14 ML of irrigation water are required per hectare of bananas per year. These data are similar to local Lakeland farmer estimates for average irrigation demand of 12 to 14 ML/ha/yr, with less used during the highest rainfall years and more during dry years.

Table 3 Monthly banana water demand and irrigation demand in the Lakeland area.

Month	ETo	Kc	Days in Month	Banana Water Requirement (mm/month)	Effective Rainfall (mm)	Irrigation Water Requirement (mm)
January	4.99	1.15	31	177.9	145.5	32.4
February	4.53	1.15	28	145.9	149.5	0
March	4.35	1.15	31	155.1	127.0	28.1
April	4.03	1.15	30	139.0	33.5	105.5
May	3.47	1.10	31	118.3	9.3	109.0
June	3.19	1.10	30	105.3	9.2	96.1
July	3.39	0.90	31	94.6	3.4	91.2
August	4.09	0.85	31	107.8	2.4	105.4
September	5.06	0.80	30	121.4	2.9	118.5
October	5.85	0.80	31	145.1	16.1	129.0
November	6.04	0.85	30	154.0	53.8	100.2
December	5.63	1.00	31	174.5	112.5	62.0
Total			**365**	**1638.9**	**665.1**	**977.4**

Table 4 Current and potential future banana irrigation water requirements at Lakeland for three different irrigation systems.

Scenario	Current	Current	Current	Current	Future	Future	Future	Future
Banana Area (ha)	1	1	400	400	800	800	1600	1600
Sprinkler Type	Conventional	Micro	Conventional	Micro	Conventional	Micro	Conventional	Micro
Irrigation Requirement	ML / 1 ha	ML / 1 ha	ML / 400 ha	ML / 400 ha	ML / 800 ha	ML / 800 ha	ML / 1600 ha	ML / 1600 ha
January	0.46	0.38	185	152	368	304	740	610
February	0.00	0.00	0	0	0	0	0	0
March	0.40	0.33	160	132	320	264	642	529
April	1.51	1.24	603	497	1208	992	2412	1987
May	1.56	1.28	623	513	1248	1024	2492	2052
June	1.37	1.13	549	452	1096	904	2196	1808
July	1.30	1.07	521	429	1040	856	2084	1716
August	1.50	1.24	602	496	1200	992	2408	1983
September	1.69	1.39	677	558	1352	1112	2709	2231
October	1.84	1.52	737	607	1472	1216	2948	2428
November	1.43	1.18	573	472	1144	944	2291	1886
December	0.89	0.73	354	292	712	584	1418	1168
Total	**13.96**	**11.50**	**5,585**	**4,600**	**11,168**	**9,200**	**22,341**	**18,399**

3.1.2 Dry Season Water Balance Results

The 2014 dry season water balance data are shown in Table 5. Reductions in water storage by the end of each month are accounted for by gains from rainfall and groundwater recharge, and losses from agricultural and natural evapotranspiration, reservoir evaporation, industrial and domestic use, and surface water outflow. The banana water use (evapotranspiration) was the largest consumer of water over the dry season (5192 ML) compared to other crops (2416 ML), surface reservoir evaporation (4193 ML) and natural evapotranspiration from soil, groundwater and vegetation combined (3556 ML) across the entire catchment (548.6 km^2) (Table 5). Dry-season surface water outflow from the catchment in rivers and creeks (4213 ML) was comparable to each of the other uses or losses (Figure 4).

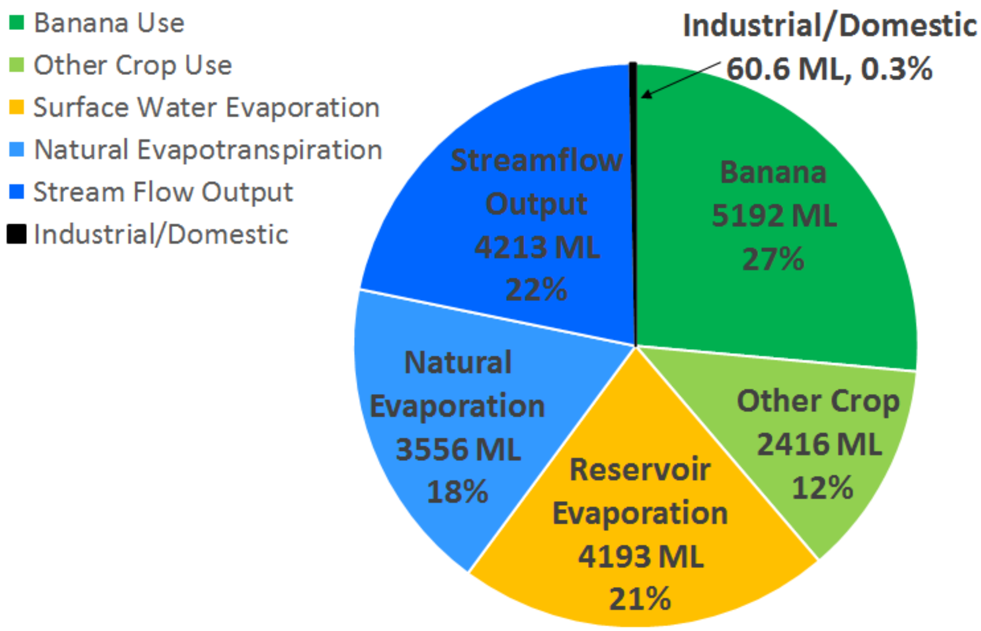

Figure 4 Total 2014 dry season water use by consumptive use or output category.

In 2014, surface water outflow (4213 ML) was 54% of direct anthropogenic uses including crop, industry, domestic uses (7669 ML), and only 35% of total anthropogenic uses if surface reservoir evaporation is included (11,862 ML). In the late-dry season (Oct-Dec) of 2014 when surface water outflows became critically low or dry, stream baseflows represented 5.5% of direct crop consumption or 3.7% if surface reservoir evaporation is included.

During the drought affected 2015 dry season, the banana water use (evapotranspiration) was the largest consumer of water over the dry season (5168 ML) compared to other crops (2405 ML), surface reservoir evaporation (4193 ML) and natural evapotranspiration from soil, groundwater and vegetation combined (3556 ML) across the entire catchment (548.6 km^2)(Table 6). Dry-season surface water outflow from the catchment in rivers and creeks (602 ML) was 7.9% of direct anthropogenic uses including crop, industry, domestic uses (7633 ML), and only 5.1% of total anthropogenic uses if surface reservoir evaporation is included (11,826 ML) (Figure 5). Stream baseflow output from the catchment area was essentially zero for the months of August to October, when critically low stream baseflows represented <0.1% of anthropogenic uses. Crop irrigation was only slightly curtailed by some farmers, and expanded in a few cases by others. However, closer to spring heads connected to the basalt aquifer, water flow remained perennial from groundwater flow, much of which was recaptured by large dams such as Honey and Spring Dams.

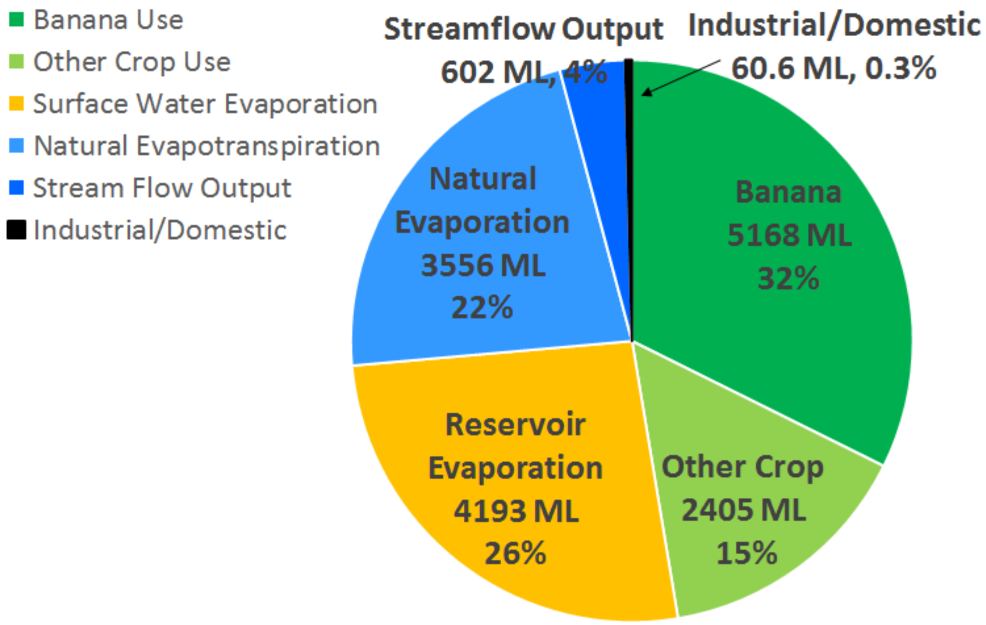

Figure 5 Total 2015 dry season water use by consumptive use or output category.

Table 5 Calculated monthly water balance storage and losses for the 2014 dry season (end of March to December).

End of Month (2014)	Rainfall (mm)	Total Water Storage (ML)	Ground water Recharge (ML)	Banana Packing (ML)	Domestic Use (ML)	ET Banana (ML)	ET Other Crops (ML)	ET Ground water (ML)	Evaporation Surface Reservoir (ML)	Surface Water Outflow (ML)
March		20499								
April	235.0	19665	1187	5.3	1.4	0	0	454	347	1214
May	1.0	17040	5	5.3	1.4	641	298	368	337	979
June	62.0	15694	313	5.3	1.4	271	126	337	319	600
July	0.0	13508	0	5.3	1.4	517	241	288	358	775
August	2.0	11615	10	5.3	1.4	579	269	313	451	285
September	0.0	9571	0	5.3	1.4	664	309	356	554	155
October	1.0	7161	5	5.3	1.4	788	367	490	666	98
November	1.0	4752	5	5.3	1.4	837	389	521	617	44
December	11.0	2453	56	5.3	1.4	895	417	429	544	63
Total	**313**	**N/A**	**1581**	**48**	**13**	**5192**	**2416**	**3556**	**4193**	**4213**

Table 6 Calculated monthly water balance storage and losses for the 2015 dry season (end of March to December).

End of Month (2015)	Rainfall (mm)	Total Water Storage (ML)	Ground water Recharge (ML)	Banana Packing (ML)	Domestic Use (ML)	ET Banana (ML)	ET Other Crops (ML)	ET Ground water (ML)	Evaporation Surface Reservoir (ML)	Surface Water Outflow (ML)
March		14349								
April	35	12737	177	5.3	1.4	580	270	454	347	133
May	0	11041	0.0	5.3	1.4	647	301	368	337	37
June	18	9730	91	5.3	1.4	480	223	337	319	36
July	0	8293	0.0	5.3	1.4	517	241	288	358	26
August	0	6658	0.0	5.3	1.4	590	274	313	451	0.5
September	0	4769	0.0	5.3	1.4	664	309	356	554	0.0
October	0	2443	0.0	5.3	1.4	794	369	490	666	0.0
November	8	154	40	5.3	1.4	799	372	521	617	15
December	316	271	1596	5.3	1.4	98	46	429	544	355
Total	**377**	**N/A**	**1904**	**48**	**13**	**5168**	**2405**	**3556**	**4193**	**602**

Total water storage under different scenarios is shown in Table 7. It was assumed the surface and groundwater reservoirs were full at the end of 2014 wet season (April 2014) and 70% full at the end of 2015 wet season (April 2015), due to major differences in wet season rainfall between years. Long term meteorological data were used for the average year. For the past condition it was assumed that no dams were in placed with no reservoir evaporation or irrigation withdrawal from surface or groundwater.

These estimated scenarios for different levels of banana production show that there is minimal available water storage for the current area (465 ha) of banana production during dry years (e.g., 2015). If banana cultivation is doubled (800 ha), during an average year there would be a water deficit from Nov-Dec. If banana cultivation is quadrupled (1600 ha), during an average year there would be a water deficit from Sept-Dec.

Table 7 Total water storage in different scenarios in different months

	Total water storage (ML)									
Scenario	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
2014	20500	19665	17040	15694	13508	11615	9571	7161	4752	2453
2015	14349	12737	11041	9730	8293	6658	4769	2443	154	271
Average year	20500	17809	15286	13283	11136	9261	7256	5034	3295	2452
Double banana (800 ha)	20500	17405	14459	12077	9576	7299	4838	2117	0	0
Quadruple banana (1600 ha)	20500	16441	12485	9200	5851	2616	0	0	0	0
Past conditions (no dams)	7250	5691	4334	3391	2299	1665	1114	532	187	370

4 DISCUSSION

4.1 Current Water Use and Future Scenarios

These preliminary water balance results for the dry-season of 2014 and 2015 indicate that limited water resources exist in the upper Laura River catchment and Lakeland Agricultural district. The basalt aquifer volume (7,250 ML, QDNRM 2013b) and current reservoir volume (13,249 ML, QDNRM 2013a) in the Lakeland district in combination are just barely sufficient to meet the current total consumptive dry season water demands (2014 estimates) from bananas (5192 ML), other crops (2416 ML) and surface reservoir evaporation (4193 ML). The remaining dry-season water balance consists of surface outflow (baseflow) from the catchment into rivers and creeks (4213 ML), and natural evapotranspiration from soil, groundwater and vegetation combined (3556 ML) across the entire catchment (548.6 km^2). During below average rainfall years like 2015, surface outflow (baseflow) from the catchment (602 ML) can be dramatically reduced.

Increases in water demand with double (800 ha) or quadruple (1600 ha) the banana crop area would lead to major water shortages in September to December months during average years, and worse in drought years. The full drawdown of both groundwater storage and surface water storage could have major impacts on 1) the integrity of the basalt aquifers, 2) the sustainability of agriculture in Lakeland, 3) downstream environmental flows, and 4) Groundwater Dependent Ecosystems.

With groundwater already over-allocated (QDNRM 2013b), many farmers are turning toward building new and bigger dams to capture wet-season floodwater as well as additional spring water during the dry season (QDNRM 2013a). The downstream impacts of additional dams and cumulative impacts on reduced baseflow in the dry season could be significant in the Laura-Normanby catchment. Any new dams proposed for the area should be investigated with 'environmental impact assessments' and 'environmental flows studies' with improved empirical field data collection to understand potential local dam impacts and the cumulative effects of damming the baseflows of multiple springs and creeks. This will be essential to avoid or minimise the cumulative impact of future water resource development. A full cost-benefit analysis of the economic and social trade-offs between various values of water, such as agricultural, domestic, stock, environmental, other commercial (fisheries, tourism), and cultural uses and values should also be included in any assessment.

4.2 Recommendations for Future Field Quantification of Water Resources

The intricate array of spring, creek, and river channels; multiple aquifers and complex stratigraphy of basalt filled valleys; dams of various sizes; and withdrawal points for consumptive use make the full quantification of water resources difficult for the Lakeland district and upper Laura catchment. The multiple beneficial uses and needs (environmental, cultural, agricultural, domestic, stock) also remain unquantified. A schematic diagram is provided in Figure 6 that shows some of this complexity. However, Figure 6 does not include the diverse range of hundreds of springs and GDE's that emerge from the basalt aquifer across the landscape. The existing water monitoring points (gauge symbol) are insufficient in number and distribution to quantify the internal use and movement of water within the catchment.

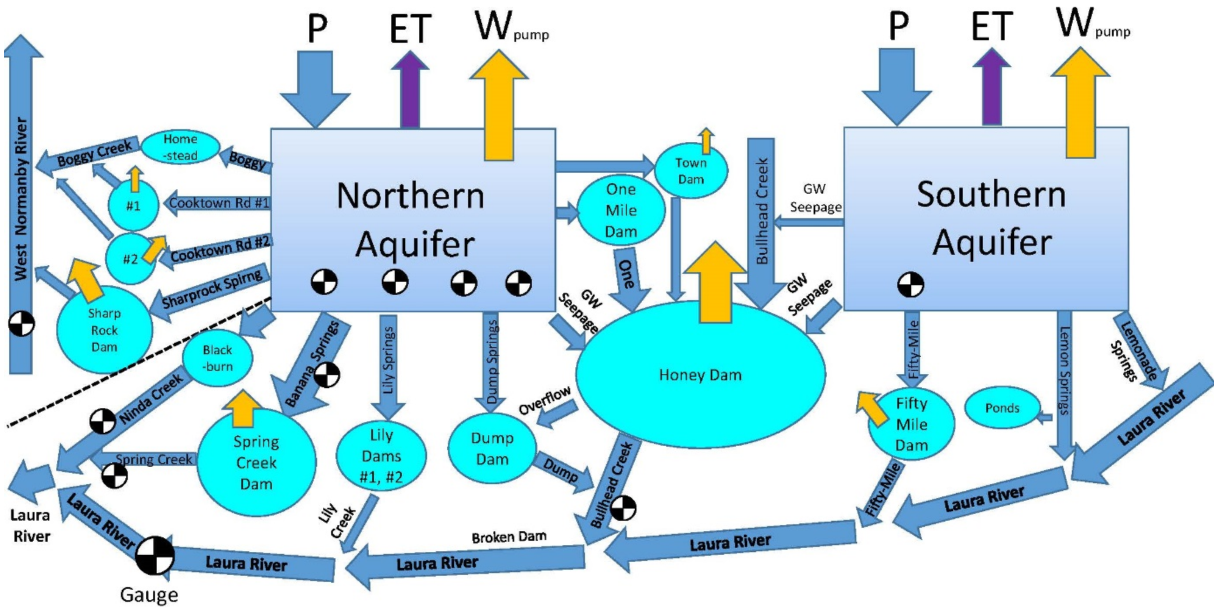

Figure 6 Conceptual model of the stream and groundwater network, and water balance, of the upper Laura River (and West Normanby) catchments and the Lakeland district. Note that evaporation from reservoir water surfaces is not shown, in addition to evapotranspiration along water courses. P = precipitation, ET = evapotranspiration, W = withdrawal of water for irrigation.

Additional detailed empirical data will need to be collected to improve the understanding of the water resources in the upper Laura catchment. The following recommendations are suggested for expanding the empirical measurement of water resources in the region.

1. Spring discharge gauging at 10+ major springs (undammed and dammed) draining from the basalt aquifers into creeks and dams at both low flow and high flood discharge.
2. Stream discharge gauging at 10+ main creeks draining from Lakeland and existing dam sites at both low flow and high flood (peak) discharge, to measure dam seepage and environmental flow rates, and compare to inflow at gauges above dams estimated from gauging or reservoir infilling rates.
3. Measuring wet season streamflow discharge during floods will allow for full-year water balances to be calculated.
4. Groundwater level monitoring at additional bore locations in both the northern, southern, and north-western basalt aquifers in addition to existing monitoring bores.
5. Improved analysis of the groundwater aquifer volumes and spring connectivity using existing detailed airborne geophysical data (mining company magnetometer data) for the Lakeland area, as well as chemical isotope tracing and dating of groundwater.
6. Dam water level gauging at reservoirs to measure changes in water height and volume over time, and thus the net water inputs, uses, losses and outputs. Water level measurements will assist estimates of storage capacity for full-year water balances.
7. Reservoir water level-volume relationships improved by more accurate estimates of volume using either lake bathymetry or airborne LiDAR at low reservoir levels.

8. The internal movement of water and dynamics within the upper Laura catchment need to be quantified, such as spring discharge, water losses along riparian zones, water withdrawal points, and water re-capture by dams.
9. Groundwater withdrawal and use rates at all major irrigation bores (regardless of location) using in-line flow meters and data recorders.
10. Permanent weather station installation at Lakeland to measure local wind speed, humidity, temperature, rainfall, solar radiation, and pan evaporation. More distributed rainfall measurement across the upper Laura catchment.
11. Actual crop water demand and usage rates for a variety of seasons and weather conditions, as well as the full variety of crops grown in the Lakeland District. Lysimeter water balance experiments could be used to measure actual crop use.
12. The ratio of groundwater vs. surface water use for irrigation, domestic and industrial demand needs to be estimated from more reliable water use rates.
13. Banana packing water usage needs to be quantified for better estimates of demand.
14. Stock water demand can be substantial and should be quantified both in Lakeland and downstream along the Laura River.
15. Domestic water usage needs to be better quantified, along with future human population expansion estimates.

4.3 Impacts of Water Resource Development on Downstream Water Users

4.3.1 Groundwater Dependent Ecosystems (GDEs) of the Laura-Normanby Catchment

The springs, downstream reaches of creeks, and the Laura and West Normanby Rivers draining from the McClean Basalt aquifers in Lakeland are Groundwater Dependent Ecosystems (GDEs). GDE's are aquatic and riparian ecosystems that require groundwater to meet all or some of their water requirements on a permanent or intermittent basis (Richardson et al. 2011). More than one-hundred individual springs emerge from the McClean Basalt that feed creeks and rivers downstream, but most springs are poorly mapped or known outside the local Lakeland area, despite their considerable size and ecological value. Almost all of the McClean Basalt springs are not currently mapped on the National GDE Atlas (http://www.bom.gov.au/water/groundwater/gde/map.shtml). The Proposal for the Cape York Water Resource Plan states that GDE mapping for Cape York was already undertaken as part of the Great Artesian Basin water resource plan (QDNRM 2016). The adequacy of this existing mapping needs to be urgently reviewed and ground-truthed as part of the Cape York Water Resource planning process. Errors and omissions in the GDE mapping are known by departmental staff, and the State of Queensland Wetland Info mapping program is currently updating their GDE identification on Cape York Peninsula to fill these known major gaps (Mike Ronan, personal communication).

Figure 7 A spring and Groundwater Dependent Ecosystem (GDE) draining from the McClean Basalt at Lakeland.

Many types of fish, crustaceans, reptiles, amphibians, invertebrates (aquatic insects), and other aquatic animals live and migrate along the perennial streams that emerge from the basalt aquifers (Figure 8). At least ten (10) species of fish are known to inhabit the upper Laura River catchment from fish surveys, including: 1) Rainbow fish (*Melanotaeniidae spendida spendida*), 2) Spangled perch (*Leiopotherapon unicolor*), 3) Purple spotted trout gudgeon (*Mogurnda adspersa*), 4) Sailfin glass fish (*Ambassis agrammus*), 5) Jewfish or Hyrtl's Catfish (*Neosilurus hyrtlii*), 6) Stripie or Pennyfish (*Denariusa bandata*), 7) Spottie or Seven-spot archerfish (*Toxotes chatareus*), 8) Bony brim (*Nematalosa erebi*), 9) Barramundi (*Lates calcarifer*), and finally 10) Sawfish (*Pristis pristis*) around the town of Laura. Barramundi (*Lates calcarifer*) regularly migrate to the base of dams in Lakeland, but are prevented from migrating further upstream (e.g., Honey and Spring Creek Dams). Large crayfish (*Macrobraciun sp.*) are known to inhabit the springs and reservoir impoundments around Lakeland. Some iconic aquatic species such as the Platypus (*Ornithorhynchus anatinus*) were observed historically but not recently in springs in Lakeland (recent Platypus observations have been documented in the East Normanby River).

a)

b)

c) d)

Figure 8 Example aquatic species along the groundwater dependent reaches of lower Ninda Creek, a) a freshwater crab (*Austrothelphusa* sp.), b) Sailfin Glassfish (*Ambassis agrammus*) c) Spangled Perch (*Leiopotherapon unicolor*), and d) Hyrtl's Catfish (*Neosilurus hyrtlii*).

The current eighteen (18) dams built downstream or on top of perennial flowing springs and creeks around Lakeland have modified and reduced the available habitat of many Groundwater Dependent Ecosystems and associated species. Over-pumping of groundwater could also affect spring output and river base-flows further downstream. Fish species are impacted by the migration barriers of dams as well as the reduced spring flow downstream of dams and groundwater bores (e.g., Figure 9; Figure 10 below). Riparian and aquatic vegetation (algae, macrophytes, trees) are also effected.

The emergent spring water from the McClean Basalt at Lakeland supports the baseflow and aquatic ecosystems of the Laura River for 80 km downstream to the township of Laura during most months of the year (e.g., Figure 9 below). The maintenance of dry season pool habitat is essential for aquatic ecosystems and species such as Barramundi (*Lates calcarifer*) throughout the Laura catchment, as well as Sawfish (*Pristis spp*.), which have been observed along the Laura River main channel by the Laura community. During the early to late dry season, as much of the lower Laura River channel goes dry (below the town of Laura), the in-river waterholes and spring water channels in the upper Laura catchment become critical refugia for fish to survive through the harsh dry season. Many fish species actively migrate into these habitats during the wet season and early-dry season to ensure population survival. Future development of water resources at Lakeland for agricultural expansion could further disrupt these Groundwater Dependent Ecosystems and push many species past their thresholds for healthy production or extinction.

Fluvial stream ecosystems are legitimate users of water, and require environmental flows as close as possible to the natural flow regime (Poff et al. 1997; Naiman et al. 2002; Bunn and Arthington 2002; Arthington 2012). In order to preserve the ecological and cultural uses of river systems and estuaries, there are natural ecological limits of hydrological alteration (Poff et al. 2009). In most cases, the majority of the natural flow regime needs to be preserved to maintain river and ecological integrity (Silk et al. 2000; Poff et al. 2009). To achieve this, consumptive water extraction should be limited to fractions of water volumes during periods of natural surplus (i.e., floods) without impeding the migration or flow of organisms, sediment or water for environmental functions. Off-stream reservoirs and flood harvesting are win-win scenarios. Natural baseflows should be left intact for ecosystem function with minimal withdrawals of baseflow during the dry season. There are numerous methods for defining and quantifying environmental flow needs for preserving the hydrological, ecological, and geomorphic functions in riverine ecosystems, as well as management options to maintain these functions (e.g., Richter et al. 1996; 1997; 2006; Poff et al. 1997; Arthington 2012; among many others).

A full research analysis of the environmental flow and stream connectivity needs of GDEs at sites around and downstream of Lakeland will be essential to managing the sustainability and equitable use of water resources in the upper Laura catchment.

4.3.2 Cumulative Effects of Numerous Dams on Downstream River Flow

Cumulative impacts or effects can be defined as "*the impact on the environment which results from the incremental impact of the actions when added to other past, present, and reasonably foreseeable future actions regardless of what agency or person undertakes such actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time."* (CEQ 1971). Unfortunately, legislation and management in Australia and Queensland have been insufficient to address the cumulative effects issues when assessing, managing or planning land use or water development activities at the catchment scale to minimise impacts to the environment (e.g., Dales 2011; QDNRM 2013a).

As an example of the cumulative effects of multiple farm dams across a catchment, "*most individual farm dams have non-measurable impacts at the [large] scale at which planning of catchment water resources is undertaken. Collectively, however, farm dams can store and extract a significant proportion of the available resource and may deny water to downstream users and to downstream aquatic environments*" (Finlayson et al. 2008). In some Australian catchments, the combined total cumulative effects of multiple farm dams and water withdrawals (surface or ground) has been documented to have significant impacts on downstream water yield, flow regimes, and aquatic and ecology (e.g., Neal et al. 2001; EA 2002; Nathan et al. 2005; Finlayson et al. 2008).

In the Laura River catchment, historic streamflow is unquantified before 1969 when the downstream Laura River gauge (105102; Figure 1) commenced. This was unfortunately *after* some of the larger dams such as Honey Dam were built as well as smaller dams on top of springs, which had already started influencing local springs and downstream baseflow by the 1970s onward to an unquantified degree. Most groundwater bores were drilled from the 1980's onward, and thus their impacts might be contained within the baseflow record 60 km downstream post-1969.

Statistical analysis of peak and baseflows at the Laura River gauge (105102) show much variability year to year depending on rainfall and climate, but no clear signal of a progressive reduction baseflows in the years and decades after dam construction had already commenced (Shellberg and Akram unpublished data). However, quantification of potential impacts remains problematic due to the quality and location of the streamflow data available. The Laura River gauge location at Coalseam Creek (105102; Figure 1) is influenced by many days of zero flowing water between pools in the dry season, making baseflow analysis difficult at this gauge 60 km downstream of water extraction points. The key metric of importance is the volume and longevity of dry season pool habitat in the river, when the river is not flowing from pool to pool but stagnant pools remain on the surface. Unfortunately, the Laura River gauge (105102) does not measure water level after the critical stage (height) measurement point is reached by the middle to late dry season, leaving the last ~1 metre of pool depth unmeasured as the pool goes dry. Thus, the gauge does not measure the full stage height hydrograph of pool drying during critical low periods (Neale Searle, personal communication).

Currently, there is a downstream (longitudinal) progressive decline of late-dry season water flow in the Laura River between Lakeland and Laura (Figure 9). This is especially the case during years with below average rainfall. During wetter years or months after the wet season (January-March) and into the early dry season (April-July), water flow increases in the downstream direction as other springs and tributaries contribute baseflow. During drought years with below average rainfall, and extended dry periods through the dry season with combined natural and human water extraction, the decline in baseflow downstream is influenced by multiple factors. These include: 1) the capture of spring water in dams at Lakeland that would otherwise flow downstream, 2) groundwater pumping at Lakeland, 3) natural loss of river water (recharge) into the Mesozoic aquifers of the Laura Basin, and 4) the use of water by riparian trees and evapotranspiration.

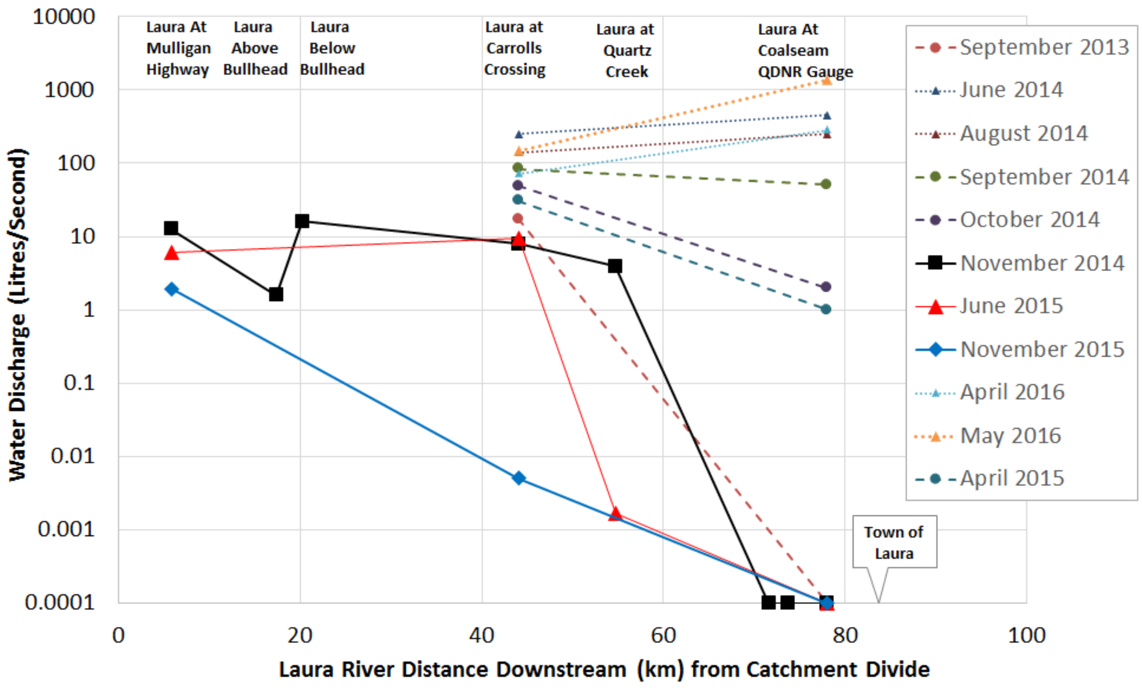

Figure 9 Downstream changes in water discharge in the Laura River during different years and seasons.

The Laura River at Coalseam Creek gauge 60 km downstream (105102; Figure 1; Figure 9) is not an appropriate location to assess the water development impacts and baseflow needs of GDE's between Lakeland and Laura. For the accurate analysis of the dry season baseflow impacts from the cumulative 18 dams and groundwater pumping at Lakeland, the environmental flow assessment points (gauges) need to be located closer to Lakeland and the McClean Basalt aquifers, as shown in Figure 6 and Figure 9 along the length of the river. Some of these gauges have recently been installed, but need to be expanded upon in the near future for more detailed planning and environmental flow guidelines. For example, water flow at the Carrolls Crossing bridge of the Laura River needs to be > 20 L/s to maintain flowing water at the downstream Coalseam Gauge through the dry season.

In some cases, the influence of individual dams on dry season base flow are readily apparent. For example, the baseflow spring discharge above and well below Spring Creek Dam (Figure 1; Figure 6) is dramatically different. Water discharge during the dry season is virtually non-existent near Spring Creek's confluence with the Laura River, as additional tributary input only increases wet season flood flows but not baseflows (Figure 10). Historically the entire length of Spring Creek had perennial spring water in the dry season, which has been significantly reduced by Spring Creek Dam and a lack of environmental flows, despite some minor dam seepage.

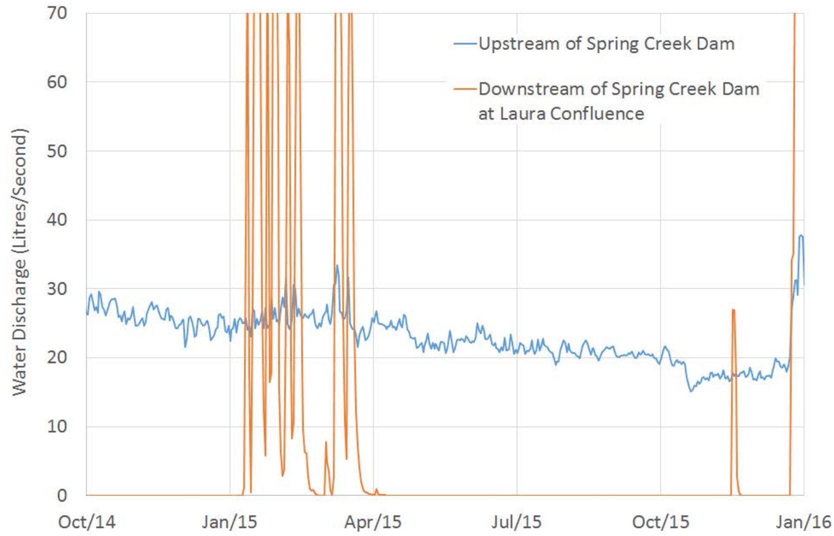

Figure 10 Baseflow spring water discharge above and further below Spring Creek Dam near Lakeland.

The *wet season flood flows* impacts of the cumulative eighteen (18) dams at Lakeland are less clear. It is assumed that these dam impacts on flood flows are manifested closest to the dam sites near Lakeland (i.e., lack of flushing flows in Bullhead Creek below Honey Dam in the wet season), and that flood impacts diminish downstream during the wet season as more ephemeral tributaries contribute wet season runoff and promote the recovery of the natural flow regime. This is clearly not the case for baseflow in the dry season (Figure 9).

In the upper Laura-Normanby catchment, a full assessment of the potential cumulative effects of water resource development is needed to manage, avoid and mitigate impacts on water quantity, water quality, and downstream groundwater dependent ecosystems.

4.3.3 Cultural Water Rights and Downstream Water Uses

Aboriginal people's rights and interests to water and land in Australia often have not been respected to support equitable and sustainable uses (Ross 2009). Aboriginal people are culturally, spiritually, socially, and economically connected to river systems. They are dependent on the health of river systems for their livelihood and cultural maintenance as well as subsistence. Additionally, they have inherent rights and values to water and the connected ecosystem health and functions on their traditional country (Strang 2002; 2004; 2005; Strang and Toussaint 2008; Jackson et al. 2005; 2014; Jackson 2006). Under current development paradigms, "*Indigenous people not only have more to lose from 'development' which erodes natural capital than do non-Indigenous people, but they also have significantly less to gain*" (Stoeckl et al. 2013). "*Subsistence activity is a key feature of the remote Indigenous customary economies, providing households with a low-cost means of supplementing incomes in economically disadvantaged regions*" (Jackson et al. 2014). "*Water resource developments that alter river flow regimes, modify habitat availability, restrict access and influence species distributions could reduce fishing and harvesting rates, in turn affecting indigenous livelihoods and well-being*" (Jackson et al. 2014; Stoeckl et al. 2013).

Traditional Indigenous economies and cultural values related to river systems cannot not be assumed to be solely protected by existing environmental flow requirements and methodologies in Australia (Jackson et al. 2014). Often, the chosen species or hydrological targets for flow protection in rivers are not the same as species or values used by indigenous people (Jackson et al. 2014). Furthermore, "*intangible indigenous social and cultural relationships with water*" (Jackson et al. 2014) can be more difficult to define and address, but are essential components of the traditional cultural landscape that European-style development infringes upon (Strang 2002; 2004; 2005; Strang and Toussaint 2008). Therefore, in the upper Laura River catchment, separate but parallel assessments are need for cultural uses of water and ecosystem services, as well as environmental flow assessments.

The equity of consumptive water use in the Laura River catchment also needs to be addressed through the Cape York Water Resource planning process. Consumptive water use is defined as water removed from available supplies without return to a water resource system (i.e. through evapotranspiration or direct consumption). In 2014, dry season (274 days) consumptive water use in Lakeland was estimated as 7669 ML, or 11,862 ML if surface reservoir evaporation is included. In contrast in the town of Laura, approximately 12.2 ML was used for town domestic supplies (225 people at 200 L / person / day). That is up to a 1000 times difference (3 orders of magnitude). For the same equivalent consumptive water used in Lakeland, a city of 140,000 to 216,000 people could be supported for domestic water (200 L/ person/day).

4.3.4 Additional Proposed Dams: Ninda Creek and West Normanby River

Additional dam proposals have been put forth for 1) a medium size dam (similar to Honey Dam in size) on Ninda Creek draining to the Laura River, and 2) a large size dam on the adjacent West Normanby River to pump water into Lakeland and the Laura River catchment (inter-basin transfer). Both of these dams would require considerable capital costs, as well as major pumping costs, which could make them economically costly compared to benefits, especially for the West Normanby Dam.

Ninda Creek remains one of the last relatively free-flowing spring-fed tributaries to the Laura River draining from the Northern Aquifer at Lakeland (Figure 6). Only a small dam (Blackburn) exists on one of the three main forks of the Ninda. The site-specific and cumulative impacts of additional dams on Ninda Creek could be significant. Ninda Creek supports important Groundwater Dependent Ecosystems (GDEs) (Figure 8; Figure 11). Damming Ninda Creek would truncate these GDEs similar to neighbouring Spring Creek, which is heavily impacted by the damming of spring water baseflow (Figure 10), preventing the migration of animals such as fish and crustaceans, and reducing environmental flows further downstream in the Laura River (Figure 9). A full environmental impact assessment is needed for any newly proposed dams to assess these local and cumulative impacts and cost-benefit scenarios.

Figure 11 Ninda Creek Groundwater Dependent Ecosystem (GDE).

The West Normanby River is a major free flowing tributary to the Normanby River and Princess Charlotte Bay. No large major dams currently exist in the Normanby catchment or on the Cape York Peninsula for that matter. Honey Dam in Lakeland is the largest current dam, and is modest in size compared to the proposed West Normanby Dam. The large West Normanby Dam proposal has been pitched to the Australian Government who funded a recent feasibility study, in the hopes of a future major government dam subsidy (FNQROO 2016). However, competition for limited federal dollars to invest in large dams across rivers in northern Australian makes the project uncertain without major private investment, as well as logistical hurdles regarding pumping water 60+ m in elevation over the catchment water divide. Furthermore, there will be a need to secure water rights and demonstrate sustainable and equitable water management (fish passage, water quality, water flow regimes, sediment transport, sedimentation, downstream estuary health, reef health) under the upcoming Water Resource Plan for Cape York (QDNRM 2016).

Comparable large size dams in northern Australia (e.g., the Ord River) have had major impacts on the health of riverine, aquatic and estuarine ecosystems due to: major changes in longitudinal connectively; changes to baseflows and flood flows; and reductions in water quality and habitat integrity (Doupé and Pettit 2002; Start and Handasyde 2002; Cluett 2005; Wolanski et al. 2001; 2004). The negative human and social impacts of large dam projects can also be significant (Head 1999; Stoeckl et al. 2013; Jackson et al. 2014). Similar changes could be expected for a dammed West Normanby River, with resultant cumulative impacts on the combined Laura-Normanby catchment, downstream wetland and estuaries, the iconic Rinyirru (Lakefield) National Park and Aboriginal Land and Princess Charlotte Bay.

The West Normanby River is a major producer of sediment in the Normanby catchment (Brooks et al. 2013). Major sedimentation of clay, silt, sand and gravel would occur behind a proposed West Normanby Dam, and significantly reduce the life span of the dam through lost reservoir capacity. The legacy and costs of removing ageing dams filled with sediment after <100 years of operation has become an international problem (Pohl 2002), as has the failure of many dams due to poor design, maintenance or sedimentation (e.g., Graham 1999).

The trapping of sediment behind dams should not be seen as a downstream sediment load mitigation or water quality management tool. Dams preferentially trap coarse sediment (sand and gravel), but still can pass fine sediment and during flood events. Fine suspended sediment (fine silt and clay <16um) associated nutrients are the primary causes of water quality impacts reaching the downstream Great Barrier Reef (Bainbridge et al. 2012; Howley 2015). Furthermore, the trapping of coarse sediment behind dams is often accompanied by increased erosion of river beds and banks downstream of dams from the '*Hungry Water*' effect, as rivers adjust to new dams and impact downstream water quality and quantity (Collier et al. 1996; Kondolf 1997). Increased channel bed and bank erosion below dams can liberate fine sediment stored in alluvial banks (e.g., alluvial gullies; Shellberg and Brooks 2013), therefore decrease water quality and impact downstream river health.

In summary, a full and balanced environmental impact assessment would be needed for the proposed West Normanby and Ninda Creek dams to assess these local and cumulative impacts, as well as a full cost-benefit analysis of the trade-offs between public governmental subsidies and private agricultural benefit, as well as the trade-offs between agricultural, environmental, and cultural uses of water.

4.3.5 Water Quality Pollution from the Cumulative Effects of Increased Agricultural Development in the Laura River Catchment

Increased agricultural production in Lakeland, such as a doubling or quadrupling of banana cultivation (Table 7), would undoubtedly result in increased fertiliser, herbicide, and pesticide pollution of downstream waterways and decreased water quality. Cumulative downstream impacts on water quality from elevated nutrients (e.g., dissolved nitrogen) have already been documented in the Lakeland district and downstream towards the town of Laura (Howley 2010; Howley and Moss 2015). Additional cumulative agricultural production will elevate this nutrient application and impact, as will additional water consumption that concentrates dry season nutrient runoff in smaller volumes of baseflow (Howley et al. 2013). Downstream concerns over increased pollution of the Laura River and the relatively pristine northern Great Barrier Reef, to which the Laura and Normanby Rivers drain, need to be taken into account with any development scenarios. Best Management Practices (BMPs) for nutrient application and use would need to follow International 1st Class Standards, otherwise the Normanby Catchment could follow the path of water quality degradation and reef degradation observed off southern GBR catchments with major agricultural development (i.e. Burdekin & Fitzroy Rivers)(Kroon et al. 2012; De'ath et al. 2012).

4.4 Water Conservation and Management Strategies

Innovative water management solutions have progressed around the globe under the pressure of water scarcity, water mismanagement, and climate change. Managing and reducing our '*water footprint*' for agricultural and urban development is essential for sustainable development under limited water resources (Mekonnen and Hoekstra 2010). In most cases, this entails living within the means of water availability in local areas, while minimizing internal and externalised costs and environmental impacts. While neoliberal growth models focus on the GDP and food export commodities, such as northern Australia food bowl proposals (The Australian Government, 2015), most local communities and small agricultural regions in Australia are better suited to cater to local and regional '*food sovereignty*' as an economic paradigm for sustainable development. Food sovereignty matches production with regional demand, maximises the ease of commercial transaction between local producers and local residents, minimises transport costs and fuel consumption, diversifies crop production and resilience, and promotes sustainable agriculture and water use in areas where the community is socially and culturally connected to (Rose and Kruse 2015).

4.4.1 Crop Water Efficiency and Type

Increasing crop water use efficiency will conserve more water for additional crop area and/or maintenance natural water flows. The banana plant is a heavy consumer of water due to its large leaf area and vigorous growth, especially in wet/dry Tropical Savannah climates with high sunshine hours and significant irrigation demand. Irrigation demand in Lakeland is 12 to 14 ML/ha/yr, or ~1100 mm of irrigation water needed on top of the ~650 mm of effective rainfall. Increasing the water use efficiency of banana irrigation in Lakeland requires further research. Micro sprinklers and drip irrigation can reduce water application rates and irrigation loss, driving efficiency above 85%. New irrigation technology may be able to increase this efficiency further, as technology is progressively improving. Irrigation scheduling may be a key factor to reduce evaporation and transpiration water losses. Avoiding water application during the day time and windy afternoons would cut water losses and increase efficiency (Figure 3), which would need improved irrigation delivery networks and scheduling.

While bananas may be the current cash crop of preference, bananas may not be the only or most efficient or profitable use of limited water resources in Lakeland. Banana yields can be up to 50 tonnes/ha in Lakeland using 12-14 ML/ha/yr, which can profit ~ $30,000/ha/yr during good times and zero when market prices are down. Other high value crops that use less water per hectare in terms of their '*water footprint*' (Mekonnen and Hoekstra 2010) may be more profitable and sustainable in the long term. Several smaller examples exist in Lakeland where other fruit crops like passionfruit and papayas and watermelon are grown with much less water per hectare, but in some cases with higher economic returns per hectare. For example, watermelons under drip irrigation and plastic can use ~ 2-3 ML/ha/yr and yield ~ 40 tonnes/ha and ~ $40,000/ha/yr.

Scaling up these potential crop options, efficiencies, agricultural intensity, and profitability deserves further attention. Other non-fruit crops with high value returns could also be investigated, as seen with sorghum, chia, and Rhodes grass fields in Lakeland or other upcoming agricultural commodities. A mix of both irrigated and rain fed agricultural crops (perennial and annual) is likely the continued future for Lakeland, following current planting trends and significant climate variability. This will balance water availability and agricultural area with environmental sustainability. The equitable use of and access to water between both small and large producers, and downstream users (cultural, environment), will be important to negotiate through the upcoming Water Resource Plan process.

4.4.2 Reducing Existing Reservoir Evaporation

Water evaporation from reservoirs can be substantial, especially in tropical and arid regions (e.g., Goldsmith and Hildyard 1984; Dingman 1994; Smith and Rodgers 2010). In Lakeland, we estimate that 4193 ML (4,193,000 m^3) is lost each dry season (April to December) from 231 ha (2,310,000 m^2) of exposed reservoir surface area. This equates to >1.815 metres of surface evaporation each year, or >1815 mm. This is within the range of potential evapotranspiration for the eastern Cape York region, 1700 to 2000 mm/year (BOM 2015). This lost water from artificial surface storage (4193 ML) is enough water to irrigate another 350 ha of bananas in Lakeland, or 1400 ha of watermelon. Or if this reservoir evaporation was reduced effectively by 80%, another 280 ha of bananas could be produced.

Technology to reduce reservoir evaporation has been around for 100 years, but is only now becoming more widely used under increased climate variability. Early technology to reduce reservoir evaporation focused on monolayers (Rideal 1925), which are chemical films one to several molecules thick that produce a diffusion barrier on the surface preventing evaporation. These layers can be made from relatively benign materials such as long chain fatty alcohols, vegetative oils, and other ingredients (Barnes 2008). They can be resistant to wind influences, but need to be reapplied periodically or every year. Numerous trials have been conducted in Australia (McJannet et al. 2008; Prime et al. 2012), and market development and large scale application are in progress. In Great Barrier Reef catchments where water quality is a major concern, additional environmental tests would be needed for application.

More recent technology has focused on providing physical barriers to surface evaporation. In the United States, polyethylene 'shade balls' have been used in many small to moderate sized drinking water reservoirs to reduce evaporation by up to 85% (Figure 12). In these cases, polyethylene plastic balls are manufactured to environmentally safe drinking water standards, resist ultraviolet light and degradation, and are coated with black carbon to deflect ultraviolet rays. The balls are partially filled with water so they do not blow away, and are blocked from flowing out spillways. Hundreds of thousands to millions of black balls (<$0.33 each) can cover surfaces of small to moderate sized reservoirs, and provide a barrier to evaporation to conserve water for additional uses. While aesthetically less pleasing, they are very effective at reducing evaporation. Shade balls still allow for oxygen exchange and would not directly kill fish in the reservoir, but would reduce algae food production. Bird habitat would undoubtedly be affected, even if on man-made reservoirs not a natural part of flyways.

Figure 12 Shade balls reducing evaporation on moderate sized reservoirs in California.

These examples may or may not be suitable for Lakeland reservoirs, and might only be applicable to small to medium sized reservoirs like Sharprock or Spring Creek reservoirs, or smaller. However, they could be cost effective and cheaper and more environmentally friendly then building new large dams. They do showcase innovative water management globally to address water loss from evaporation in artificial reservoirs. The high evaporative loss of water from Lakeland water reservoirs also highlights the need to investigate alterative storage options that are not subject to major evaporative losses. In this case, the 'conjunctive use' of water can be used as the combined use of surface water and groundwater supplies to meet overall water supply and natural resource management objectives. In the example reviewed below, floodwater captured in dams in the wet season can be recharged and injected into groundwater aquifers for prolonged storage that avoids losses to evaporation, while managing seepage losses.

4.4.3 Conjunctive Use of Surface and Ground Water Resources as a Water Management and Conservation Paradigm

'**Conjunctive Use**' of water is the combined use of surface water and groundwater supplies to meet overall water supply *and* natural resource management objectives.

'**Conjunctive Management**' of surface water and groundwater entails this conjunctive use, but depends on the long-term use of monitoring data, scientific studies, and understanding hydrological and hydrogeological process to drive adaptive management of the combined water resources (Figure 13; Dudley and Fulton 2005; Brodie et al. 2007).

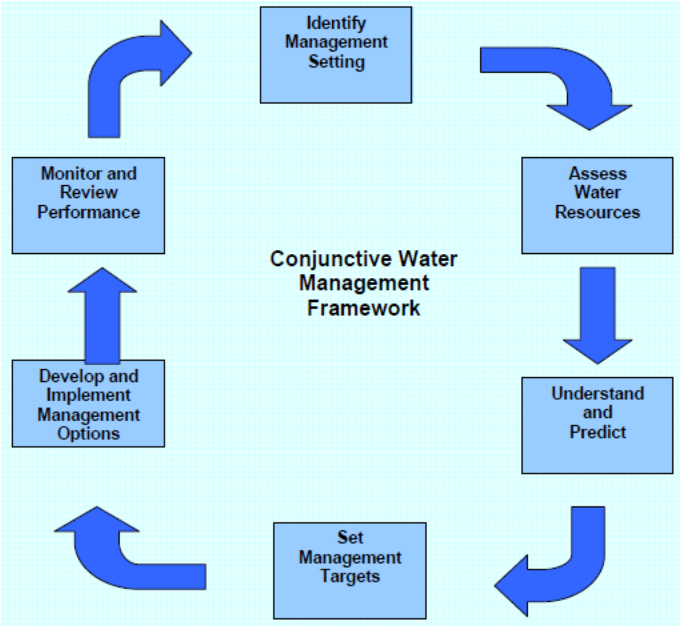

Figure 13 The adaptive management framework for conjunctive water management (from Brodie et al. 2007).

The conjunctive use of surface and ground water storage can provide a reliable buffer during periods of water scarcity at the seasonal, annual or multi-year time cycles. In conjunctive use field practice, surface water resources are actively stored in groundwater aquifers or basins in wet years and seasons, and are withdrawn from aquifers and reservoirs during dry periods following close monitoring. This is called '*Aquifer Storage and Recovery*' (ASR), or in Australia, '*Managed Aquifer Recharge*' (MAR) (Figure 14). Surface water can be stored in groundwater aquifers via either direct injection wells for confined aquifers, or via infiltration basins for unconfined aquifers. If surface water is significantly contaminated, then it may need to be treated before injection (Figure 14), but this should not be a major issue or cost during wet season floods in the upper Laura catchment. ASR has been used successfully in various locations in Australia in unconfined, semi-confined and confined aquifers for irrigation, urban, and environmental water needs, for example, since the 1960s on the Burdekin Delta, Queensland (Dillon et al. 2009).

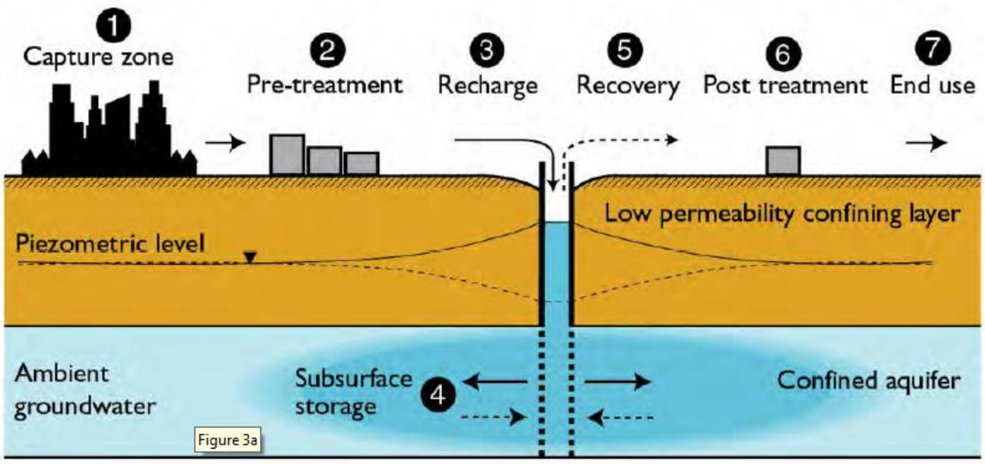

Figure 14 A conceptual model of 'Aquifer Storage and Recovery' (ASR) in a semi-confined or confined aquifer (from Dillon et al. 2009), with pre- and post-treatment (steps 2 and 6) only needed for contaminated urban water, and the capture zone (step 1) consisting of multiple possible sources such as freshwater reservoirs, streams, or runoff.

With the increasing global scarcity of freshwater following increased population demand, the conjunctive management of surface and groundwater for irrigated agriculture becomes essential to ensure both economic and environmental sustainability through the efficient use and management of water (e.g., Nevill 2008; Singh 2014). Conjunctive management of water can help take pressure off any one source, improving reliability and sustainability. Most importantly, the efficient conjunctive use of water can ensure that all beneficial water uses are provided with equitable and sustainable water distribution, such as with the environmental, cultural, domestic, and economic uses of water. However, the mismanagement of water with poorly conceived conjunctive use in irrigated agricultural (i.e., mining multiple sources of water) can have major environmental impacts, as well as impacts on the groundwater aquifer, springs, GDE's, and other users (Nevill 2008; Singh 2014).

Conjunctive use of surface and groundwater is already occurring spontaneously by default in the Lakeland District, where groundwater is used to alleviate the seasonal deficiencies of surface water and climate uncertainties at the annual and multi-year scale. However, the *conjunctive management* of water in Lakeland is in its infancy, with considerable groundwater overdraft, no proactive storage of surface water in groundwater aquifers, and slowly improving monitoring or research to drive adaptive decision making. Currently the McClean Basalt aquifers are not used to their maximum water storage and recovery potential to ensure sustainable water yields for both irrigation and environmental flow needs of GDEs.

Aquifer Storage and Recovery (ASR) in the McClean Basalt at Lakeland could be a cost effective and efficient management tool to ensure sustainable water supplies for agriculture as well as maintaining downstream environmental flows in springs, creeks and rivers of GDEs. ASR at Lakeland could help avoid the higher costs of dam construction, reservoir piping and pumping, reservoir siltation, and environmental impacts of building new large dams (Dillon et al. 2009). The costs of double pumping water for ASR could be minor in comparison, and be offset by using renewable power sources.

Lakeland is currently investing in a major solar farm to be built in 2016/2017 by the company Coenergy. It will include, 13-megawatt PV (photovoltaic) project with 41,000 solar panels covering 45 ha, along with 5 MW-hr battery storage. It will provide clean power locally and to the grid for 25 years. Furthermore, a private company is researching the potential for a major wind turbine farm in Lakeland, which has substantial wind energy potential. These local renewable energy sources would provide cheap and reliable renewable energy that could offset additional pumping costs for aquifer storage and recovery (ASR), helping to develop a truly sustainable agricultural economy.

ASR in the McClean Basalt at Lakeland would need to occur in 3-4 separate aquifer management units and sub-catchments, due to the complexity of the geology and aquifers and reservoir locations. Property owners would pump excess floodwater into their local aquifer to recover later from bores or groundwater seepage into their local dam. However, this would require cooperation between neighbours. The current system of medium sized dams and reservoirs at Lakeland enables the capture of floodwater runoff during the wet season. Additional 'floodwater harvesting' from run-of-the river pump sites (without dams) during moderate flood levels could also be used for ASR. During average and above average rainfall years, this floodwater during the first half of the wet season could be harvested or captured, and injected via wells into the McClean Basalt aquifers upstream of the dams. Infiltration basins could also be used rather than bores to recharge aquifers with surface water, specifically for unconfined sections of the aquifers. Follow up rains and groundwater seepage could ensure that the reservoirs refill again on good years, to match the full recharge of the aquifers. Since most of the existing dams are downstream of springs and the aquifers, these reservoirs would recapture much of the groundwater lost to leakage, in addition to the recovery wells. The uncaptured leakage and releases from a full aquifer would benefit downstream groundwater dependent ecosystems, which would also benefit from improved regulation of environmental baseflow released below full dams.

Storage of floodwater in underground aquifers would reduce the loss of water to evaporation in surface reservoirs, which is quite high in this part of the tropics and is estimated to be > 4193 ML (1815 mm) per year currently. The costs of ASR could be compared to the installation and maintenance of evaporation barriers across >231 ha of reservoir surface (see above). The excess water stored underground in wet years could be used during both the dry winter season and below average rainfall years to meet agricultural irrigation demand and environmental flow needs of springs and downstream GDEs. Proactive baseflow releases of extra flood water stored in the aquifers and reservoirs could also be conducted below dams and irrigation areas during the dry season to meet legislative environmental flow needs of GDEs normally maintained by natural groundwater and spring flow output.

Conjunctive management of combined surface water and groundwater resources at Lakeland would require significant cooperation and sharing of water resources between agricultural users in 3-4 separate aquifer management units with downstream reservoirs. Cooperation will ensure existing rights and future equity and access to water resources across property boundaries. For example, captured water that was injected into bores in the aquifers on the primary property of capture, or neighbouring properties, would need to be re-allocated back to the original water permit holder, but with adjustments and allowances for the points of re-withdrawal on primary or neighbouring properties. Thus cooperative agreements would need to be established so that the Lakeland community was working together with the existing infrastructure to make effective conjunctive management a reality (e.g., a Cooperative Irrigation District). Downstream ecological and cultural users of water would also need to be part of the cooperative water management to ensure the equitable use of water.

Detailed monitoring and research of water resources at Lakeland would be essential for functional and equitable conjunctive water management. Monitoring and research would drive adaptive management toward both more reliable and sustainable irrigation supplies and environmental flows. This would help avoid past issues with the overdraft of both ground and surface water supplies through mismanagement or 'tragedy of the commons', which has led to agricultural water shortages and impacts on Groundwater Dependent Ecosystems.

4.4.4 Floodwater Harvesting and Off-stream Storage Locations

The harvest of floodwater via pumping water in the wet season during flood events into off-stream storage reservoirs or groundwater aquifers (aka 'Water Harvesting') is potentially a sustainable alternative to damming rivers and creeks across their main channels with resultant major environmental impacts. Pumped and diverted floodwater could be piped into existing dams or off-stream storage reservoirs on ephemeral tributaries or valley depressions. Or, water could be pumped into ground water aquifers, such as with 'Aquifer Storage and Recovery' (ASR) mentioned above.

Pumping of floodwater from creeks and rivers could be achieved through pumps in deep pools on stable bank locations, which is preferred to minimise impacts to fish passage and sediment transport. Any pumps or diversions would need highly functional fish screens to avoid fish entrapment or entrainment. Less preferred, low head weirs with stable platforms could be used to pump water from. However, any low-head diversion weirs would need highly functional fish ladders to ensure fish passage, as well as release gates to flush trapped sediment annually from the weir area.

Water pumping rules could be instated to dictate the streamflow discharge thresholds above which water could be pumped during floods, months of diversion (Jan-Mar), as well as total volume of diverted water. This would essentially follow recommendations for '*turning instream flow water rights upside down*' (Silk et al. 2000). Pumping or diverting <10% of the floodwater volumes during episodic flood events into off-stream storage locations will have far less impact on downstream ecosystems, and other water users, than capturing all the floodwater in instream dams and only providing the absolute minimum dry season baseflows to downstream users (Richter et al. 2006; Poff et al. 2009; Arthington 2012).

In the upper Laura River catchment and Lakeland, there are several opportunistic locations and possibilities for floodwater harvesting and off-stream storage locations:

- Laura River or Ninda Creek floodwater harvesting into existing dams (top-up of Honey Dam, Spring Creek Dam, or Sharprock Dam),
- Laura River or Ninda Creek floodwater harvesting into basalt aquifer bore fields using 'Aquifer Storage and Recovery' (ASR).
- West Normanby floodwater harvesting at a deep bedrock pool, or low-head diversion weir and pump location (with fish ladders and sediment passage), to pump and divert wet season floodwater into existing dams in Lakeland (top-up of Honey Dam, Spring Creek Dam, or Sharprock Dam), and/or basalt aquifers bore fields using 'Aquifer Storage and Recovery' (ASR).

Several proposals already exist in the Lakeland area for 'water harvesting' during wet season floods, including 1850 ML of floodwater from the Laura River and 3000 ML of floodwater from the West Normanby River (QDNRM 2013a).

5 CONCLUSIONS

A preliminary dry-season (April-December) water balance for the upper Laura River catchment and Lakeland agricultural district was developed to help inform decision making on water resource development, expansion of banana agriculture, scenario trade-offs between upstream and downstream users of water, and the environmental and cultural impacts of water resource development. This water balance builds on past research and monitoring in the district. However, the water balance will need to be continually updated in the near future to improve the accuracy and detail of the water balance as more local data become available on the internal dynamics of the system.

The results calculated for Lakeland estimated that 12 to 14 ML of irrigation water are required per hectare per year of bananas, which is similar to local Lakeland farmer estimates for irrigation demand. For the current 465 hectares of banana cultivation, banana water use (evapotranspiration) was the largest consumer of water (5192 ML) over the 2014 dry season compared to other crop water use (2416 ML). Surface reservoir evaporation (4193 ML) from the relatively small reservoir area (231 ha) was high compared to natural evapotranspiration (3556 ML) from soil, groundwater and vegetation combined across the entire catchment (548.6 km^2). In 2014, surface outflow from the catchment in rivers and creeks (4213 ML) was less than half (43%) the volume of direct anthropogenic uses including crop, industry, domestic uses (9723 ML); and only 30% of the volume of total anthropogenic uses if surface reservoir evaporation is included (13,916 ML). In the drier 2015, surface water outflow (602 ML) was 7.9% of direct anthropogenic uses including crop, industry and domestic uses (7633 ML), and only 5.1% of total anthropogenic uses if surface reservoir evaporation is included (11,826 ML). In the late-dry season months of 2014 and 2015, stream baseflows represented 4% of direct crop consumption in 2014 and 0.1% of direct crop consumption in 2015. However closer to spring heads connected to the basalt aquifer, water flow remained perennial from groundwater flow, much of which was recaptured by dams with minimal seepage.

These preliminary water balance results for the dry-season of 2014 and 2015 indicate that limited water resources exist in the upper Laura River catchment and Lakeland Agricultural district. Under the current scenario (465 ha of bananas), there is a water deficit for banana irrigation during dry years like 2015, with only minimal surplus during average years. If banana cultivation is doubled (800 ha) or quadrupled (1600 ha), then during an average year there would be a water deficit from Nov-Dec or Sept-Dec, respectively.

With groundwater already over-allocated, many farmers are turning toward building new and bigger dams to capture wet-season floodwater and additional spring water during the dry season. However, the downstream cumulative effects of additional dam building could be significant in the Laura-Normanby catchment, with impacts on downstream water users such as: other irrigators; domestic water supplies; stock water use of stream waterholes; springs feeding Groundwater Dependent Ecosystems; river riparian ecosystems; migratory fish and habitat use; the Laura township; and Aboriginal People who live along and use the Laura River for sustainable livelihoods and cultural integrity. Any new dams proposed for the area should be investigated with 'environmental impact assessments' and 'environmental flows studies' with improved empirical field data collection to understand potential local dam impacts and the cumulative effects of damming the baseflows of multiple springs and creeks. A full cost-benefit analysis of the economic and social trade-offs between various values of water should also be included in any assessment, such as agricultural, domestic, stock, environmental, other commercial (fisheries, tourism), and cultural uses should also be included in any assessment.

As an alternative to building new dams, there are many ways to improve water management and use efficiency in the Lakeland district through: 1) increasing crop water efficiency and changing the types of crops grown, 2) reducing reservoir evaporation through technological advances, 3) utilising 'conjunctive use' between surface water and groundwater resources through 'Aquifer Storage and Recovery', and 4) floodwater harvesting in the wet season by pumping flood water into off-stream storage reservoirs and/or basalt aquifers. These alternatives could be cost effective compared to the higher costs of dam construction, reservoir piping and pumping over large elevation heads, reservoir siltation, and externalised environmental and economic impacts of building new large dams. These management tools could help ensure sustainable water supplies for future agricultural as well as maintaining downstream values, and can create 'win-win' situations.

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