Modelling recharge to a Tropical karst feature.

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EXECUTIVE SUMMARY

The aim of this study was to quantify the point recharge that occurs via swallow holes developed in the unconfined Tindall Limestone aquifer in the Katherine region of the Northern Territory. The objective was to construct a rainfall–recharge relationship for Sculpture Cave that could be used to model the recharge occurring via swallow holes at other sites in the region. Sculpture Cave was selected as the study site as it was the only swallow hole in the region that had been equipped as a gauging station.

The gauging station (G8140025) at Sculpture Cave consisted of an Acoustic Doppler Current Profiler (ADCP) mounted at the cave entrance. A preliminary analysis of the ADCP data in January 2009 showed that whilst the ADCP worked and was able to collect flow data the meaningfulness of this data was questionable. Subsequent fieldwork was undertaken to investigate this with the study utilizing water level loggers, field inspections, a level survey and a time-lapse camera system. The study identified that the flow at the cave entrance would only be active after water has entered the system through the other swallow holes. This meant that the ADCP at its location at the cave entrance did not give a good indication of the amount of point recharge occurring in the area.

It became necessary to investigate other means to achieve the aim of this project. A previously developed rainfall–recharge relationship developed by Jolly et al (2000) was applied to the Sculpture Cave catchment. This resulted in modeled estimates of water year recharge to the swallow holes in the Sculpture Cave area for the corresponding historical rainfalls (see Figure 57). Further analysis of this modeled data found that recharge via swallow holes in the vicinity of Sculpture Cave may be contributing of the order of 15% of the spring inflow into the Katherine River over the period 1884 to 1999.

The main hydrologic characteristic that impacts on recharge has been identified to be the great variability in rainfall. A Monte Carlo analysis of the long term rainfall record (119 years) was undertaken. This analysis indicated that the mean rainfall of 1240mm for the 10 year period from 1996/97 to 2005/2006 lies at approximately the 99.7th percentile for decadal rainfall (i.e. the ten year period is very wet). This is the period when the ADCP was operational.

The modelling of recharge through the swallow holes in the Sculpture Cave area undertaken in this study assumed that all of the runoff from the catchment recharges the Tindall Limestone aquifer through the swallow holes. It is possible that a significant percentage of surface runoff may flow past the swallow holes (see Figure 52). Available data does not allow a determination of the percentage of the runoff that will bypass the swallow holes. A more comprehensive method of measuring recharge to the group of swallow holes near Sculpture Cave has been recommended. It is proposed that this be done by installing one gauging station upstream and one downstream of the Sculpture Cave area to capture the flow entering the swallow holes and the flow exiting this zone when the swallowing capacity is exceeded. This study identified the importance of thorough groundwork before deploying equipment in the field. If this field inspection is not undertaken properly then the data acquired may prove to be meaningless. A thorough examination of the catchment needs to be undertaken prior to the installation of these gauging stations. The data acquired from these gauging stations will then
enable the recharge that is occurring through swallow holes in the area around Sculpture Cave to be more accurately quantified.

The method developed Jolly et al (2000) and Knapton (2006) that enabled recharge in the Sculpture Cave area to be estimated should be applied to other swallow holes, or groups of swallow holes, in the unconfined Tindall Limestone aquifer in the Katherine region to model recharge. It will then enable the significance of this recharge mechanism to be better quantified and also identify other swallow holes where further detailed work is warranted.
LIST OF ACRONYMS

ADCP  Acoustic Doppler Current Profiler
GDE  Groundwater Dependent Ecosystem
NAIF  North Australian Irrigation Futures
NRETAS  Department of Natural Resources, Environment, The Arts and Sports
NT  Northern Territory
WAP  Water Allocation Plan

GLOSSARY

Aquifer  Rock formation that is able to store water which can be extracted
Diffuse recharge  Recharge that occurs to the aquifer slowly via infiltration through the soil matrix.
Karst  Landscape shaped by the dissolution of typically limestone or dolomite.
Point recharge  Recharge that occurs to the aquifer rapidly via infiltration into conduits in the subsurface, typically occurs at swallow holes.
Swallow hole  Naturally occurring depression or hole in the surface topography caused by the removal of soil and/or bedrock by water.
Water Year  1 October to 30 September
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1. INTRODUCTION

1.1 RATIONALE

In recent years Northern Australia has been the target of a number of Commonwealth government initiatives to increase our knowledge of the region’s water resources and also to investigate the potential for increased agricultural development. The reduced water availability in the more populated southern regions of Australia due to drought has resulted in the perception that Northern Australia with its abundant rainfall is the “future for the nation’s food production” (Morris 2009). The latest of these is the CSIRO’s Northern Australia Sustainable Yields Project which was essentially on audit on the water resources of Northern Australia (NASY 2009). The potential of agriculture has been brought to the forefront in recent years by the Northern Australia Land and Water Taskforce. This taskforce is an independent body whose role is to examine the potential for new water-intensive developments in Northern Australia (NALWT 2009). The Northern Australia Irrigation Futures (NAIF) project running from 2003 to 2007 through the CRC for Irrigation Futures examined ways in which irrigated agriculture could proceed in Northern Australia (NAIF 2007).

One of the key points raised in these Commonwealth government funded studies is that the perception of Northern Australia as the land “where the rain always falls” is misleading (Goode 2009). The rainfall in Tropical Northern Australia has a strongly monsoonal weather pattern with approximately 90% of the rainfall occurring in a 5 month period. The rest of the year is significantly dry with many rivers ceasing to flow. The river systems which are active during the dry season are fed by groundwater and support unique and diverse groundwater dependent ecosystems (GDEs). These GDEs are extremely susceptible to exploitation of the regional groundwater resources (NRETAS 2009).

Katherine is the third largest population centre in the Northern Territory (NT) and is located on the banks of the Katherine River. The region around Katherine has seen significant agricultural development take place in recent years. These developments draw heavily on groundwater from the unconfined Tindall Limestone aquifer. In the dry season the flow in the Katherine River is maintained through discharges from this groundwater. This has lead to the development of a Water Allocation Plan (WAP) for this aquifer which was officially declared by the Federal Minister for Natural Resources, Environment and Heritage, on the 19th August 2009 (NRETAS 2009).

The basis of managing a groundwater resource lies in the understanding of the hydrological cycle. For a groundwater system there are three main components: recharge, discharge and storage. The unconfined Tindall limestone aquifer near Katherine is a special type of groundwater system known as karst. A karst aquifer system behaves differently from a typical groundwater system in that the main groundwater processes occur within a system of conduits and caves culminating in spring outlets. This takes place in addition to diffuse groundwater flow through the soil matrix. The findings of the NAIF project state that if irrigation is to be expanded in Northern Australia then it “requires improved understanding of groundwater, river and catchment attributes” (NAIF 2007). This is particularly important in a karst system such as the unconfined Tindall limestone. Recent work by Knapton (2006) has identified that the current lack of knowledge of direct recharge is a major weakness in the current...
groundwater model that has been developed for the Tindall Limestone aquifer. Direct recharge to this aquifer is normally via swallow holes such as Sculpture Cave.

Sculpture Cave is a karst feature developed in the Tindall Limestone where significant point recharge has been shown to occur. Sculpture Cave is located within the area covered by the Katherine Water Allocation Plan for the Tindall Limestone (NRETAS 2009). The Water Resources Division of the NT Government, currently in the Department of Natural Resources, Environment, The Arts and Sports (NRETAS), in the wet season of 1996/97 attempted to quantify the recharge that occurred through this particular cave. Significant flows (8 cumecs) were measured and the gauging station (G8140025) at the site was reopened for the wet season of 2000/01 and was kept in operation until 2005/06 when repeated equipment issues lead to the closure of the site. Flow records were captured by an Acoustic Doppler Current Profiler (ADCP) which was installed at the entrance to the cave.

1.2 AIM & OBJECTIVE

The aim of this study was to quantify the point recharge that occurs via swallow holes (a type of sinkhole) developed in the unconfined Tindall limestone aquifer in the Katherine region of the NT. The objective was to construct a rainfall–recharge relationship for Sculpture Cave that could be used to model the recharge occurring via swallow holes at other sites in the region. Sculpture Cave was selected as the study site as it was the only swallow hole in the region that had been equipped as a gauging station.
2. LITERATURE REVIEW

2.1 LOCATION

Sculpture Cave is located within Cutta Cutta Caves Nature Park near the township of Katherine in the Northern Territory (see Figure 1). The Nature Park was established in 1967 and has become a major tourist attraction. It is located 30km southeast of Katherine and covers an area of 15 square kilometers. The Nature Park contains the entrances to a number of cave systems the most prominent being Cutta Cutta Cave. The Park is bounded by the Stuart Highway to the north, by the Tindal RAAF Air Base to the west, and by land zoned for rural use to the south and east. The traditional owners of the land the Park is on are the Jawoyn Aboriginal people who regard the Park as having significant cultural value to them. There is evidence of a long history of human occupation with campsites and stone artifacts having been found within the confines of the Park (Parks & Wildlife Commission 2000).

![Figure 1](image)

Figure 1 Location of Cutta Cutta Caves Nature Park (Parks & Wildlife Commission 2000)

The Park overlies the Tindall limestone. This formation which consists of mainly permeable grey limestone was developed in the middle Cambrian period more than 500 million years ago. In the Katherine area a tropical karst landscape has developed.

Karst formations and cave systems have been developed through the chemical weathering/dissolution of the limestone. This process is most active at or just below the water table where the water movement is slow and the acidity is highest (Milanovic 2004). The extensive cave
systems in the Park, as shown in Figure 2 are a measure of the intensity and persistence of these karst processes (Lauritzen & Karp 1993).

![Figure 2](image)

It should be noted that the management plan developed for the Nature Park in 2000 by the Parks and Wildlife Commission of the Northern Territory stated that:

*Further study to improve understanding of the hydrological dynamics of the cave systems and the catchments which influence them will be actively encouraged.*

### 2.2 CLIMATE

The Katherine region being located in the wet-dry Tropics experiences two distinct seasons, the wet season and the dry season. The wet season starts in December and finishes in April. Rainfall in the region results from the influence of the monsoon and low pressure weather systems. These low pressure systems can also result from decaying Tropical cyclones. The rainfall for the annual water year (October to September) has a mean of 980mm with a low of 364mm and a high of 1990mm (NRETAS 2009). Daily rainfall was first recorded in Katherine in 1873 (Bennet & Hearnden 2005). The variability in rainfall is high and in the period in which rainfall records have been recorded the region has experienced both prolonged wet and prolonged dry periods. In the last decade the region has experienced some of the wettest years on record.
Temperatures in the Katherine area range from a mean annual maximum of 34°C to a mean annual minimum of 20°C with the highest maximum temperatures being reached in the months of October and November where the daily maximum often reaches 38°C. The annual pan evaporation rate is approximately 3000mm which exceeds annual rainfall (NRETAS 2009).

2.3 KARST

The outcropping of Tindall Limestone over which the study area is located forms a distinct and extensive karst terrain.

Karst terrains form in soluble rocks typically carbonates such as limestone or dolomite. These terrains arise due to the solubility of the, in this case, limestone being acted upon by a number of geological processes known collectively as karstification, a slow process that operates over geological time. The limestone being composed of mainly calcium carbonate (CaCO$_3$) undergoes chemical dissolution. This in conjunction with the erosive power of water leads to the formation of caves and conduits. The formation of these caves and conduits is guided by geological features in the parent material. Weaknesses such as folds, faults, joints and bedding planes assist in the passage of water and over time through a combination of dissolution and erosion will form a network of caves and conduits in the parent material which is characteristic of karst terrains (Milanovic 2004).

Groundwater flow in karst regions for the most part is independent of topography but rather is directed by these geological formations and structures. The topography will however define the hydrologic base level which affects the regional drainage pattern (Goldscheider & Drew 2007).
All aquifers are heterogeneous to some extent. However the heterogeneity of karst aquifers is extreme. Groundwater flow may occur in large quantities in conduits and caves, yet there may be massive, unproductive rock only a few metres away (see Figure 4). Heterogeneity is a major issue in karst hydrogeological investigations (Goldscheider & Drew 2007).

There are very few similar studies published regarding the type of project attempted here. This is because typical studies in karst focus on the spring outlets as they are easier to locate and cheaper to monitor (Goldscheider & Drew 2007). It is very costly and time consuming to try and locate all the inputs to a highly heterogeneous karstic aquifer. A study in Lake Seminole made use of dye studies and an ADCP to quantify water disappearing from the dam reservoir due to sinkholes further upstream (Torak 2006). However this ADCP usage was conventional in that it was recording constant discharge measurements, not sporadic long-term inflow measurements as was measured for this study.

A speleological assessment of the area by the NT Government in 1993 did not include Sculpture Cave but incorporated two nearby caves, Tindall Cave and Cutta Cutta Caves. This study observed that the “Tindall karst plain is an exhumed paleokarst surface” (Lauritzen & Karp 1993) with most of the karstic features such as swallow holes having been developed before the Cretaceous period (Lauritzen & Karp 1993).

A regional FEFLOW groundwater model has been developed for the aquifer in the Tindall Limestone (Knapton 2006). In the report concerns are raised over the lack of understanding of the dominant recharge mechanism which is stated to be by swallow holes. To overcome this in the model the recharge was estimated as diffuse recharge. This approach works for dry years when there is little surface runoff but the model had issues matching the spring flows into the Katherine River in wet years. In the report direct recharge from the swallow holes was identified to be a major component of

![Figure 4 Schematic of typical karst aquifer system (Goldscheider & Drew 2007).](image-url)
the water balance for the system and it was recommended that there is a need for it to be better understood.

2.4 REGIONAL GEOLOGY

The regional geology as reported below is primarily a summary of the work by Tickell (2005) except where otherwise noted.

The unconfined Tindall limestone in which Sculpture Cave has been formed is an outcropping of the Tindall Limestone Formation which is the basal formation of the Daly Basin. The Daly Basin is a sedimentary sequence which is approximately 350 kilometres long and 75 kilometres wide with a maximum recorded thickness of over 700 metres. The formation is present throughout the Daly Basin. It is also laterally continuous with equivalent formations in the Georgina and Wiso Basins to the south. In the Georgina Basin its equivalent is the Gum Ridge Formation and in the Wiso Basin it is the Montejinni Limestone (see Figure 5) (Knapton 2006).

![Figure 5](image-url) Regional extent of the Daly Basin and the Tindall Limestone (or equivalents) (Tickell 2005)
The Tindall Limestone being the basal formation is overlain by the Jinduckin Formation and then by the Ooloo Dolostone Formation (see Figure 6). The Tindall Limestone being composed of primarily limestone, the Ooloo Dolostone being composed of primarily dolostone and the Jinduckin Formation being composed of mainly siltstone.

Cretaceous sedimentary rocks formerly blanketed the whole area with the present day landscape being largely erosional in nature due to the dissection of the Cretaceous cover. The current landscape contains areas that closely approximate the contact between the Cretaceous cover and the underlying Tindall Limestone.

**Figure 6** Geology of the Daly Basin (NASY 2009)
The Tindall Limestone and the overlying Jinduckin Formation contact conformably across the Daly Basin. Breccias and cave formations at the top of the Tindall Limestone indicate local exposure which would have required a break in sedimentation before the Jinduckin Formation was deposited (Kruse et al 1994). The caves that lay beneath the Cutta Cutta Caves Nature Park have been formed in the Tindall Limestone (see Figure 7).

**Figure 7** Conceptual groundwater model for the Katherine region (not to scale), note that Sculpture Cave is located adjacent to Cutta Cutta Caves (NRETAS 2009, p71 of WAP)

The Tindall Limestone in parts is overlain unconformably by early Cretaceous rocks. The sub-horizontal beds of this Cretaceous cover are composed primarily of clay, claystone and sandy clay whilst also containing sandstone, sand and clayey sand.

### 2.5 HYDROGEOLOGY

In a speleological survey by Lauritzen and Karp (1993) several cave systems in the Tindall Limestone in the Katherine area were mapped and it was found that they dominantly trend northwest to southeast. Two of these cave systems were within the Cutta Cutta Caves Nature Park. The fractures they have developed on are parallel to the strike of the beds. The consequence of this is that groundwater flow towards the Katherine River is enhanced. The network of fractures and finer solution cavities use these cave systems act as drainage collectors from which water discharges at major springs on the banks of (see Figure 8) and through the bed of the Katherine River.

Water movement through cave systems can be rapid. This was shown in a dye tracing test which took place just north of the Katherine River (Karp 2005). Dye was released at sinkholes located 2.5km and 4km from the river, the dye took 2 and 7 days respectively to reach springs on the bank of the Katherine River.
Across the region recharge to the Tindall Limestone aquifer is highly variable. Recharge varies depending whether the Tindall aquifer is covered by the younger formations of the basin and also varies depending on the amount of rainfall that occurs in the area. Around the basin margins where the Tindall Limestone outcrops recharge rates are highest (Tickell 2005). Sculpture Cave occurs in such an area.

Recharge to the unconfined Tindall limestone aquifer in the Sculpture Cave area occurs in several ways. Rainfall that falls on the karst surface results in diffuse recharge which infiltrates into the aquifer. In addition to this there is surface runoff from the upstream catchment, a large percentage of which is underlain by the low permeability siltstone of the Jinduckin formation, enters the karst area and enters the aquifer at discrete points as direct input. The runoff stream can enter the aquifer via a single point (called a swallow hole) where the water will enter a distinct hole or cave entrance, or it can enter the aquifer along a losing stream reach which is where the stream flow diminishes incrementally downstream until the channel is dry, this occurs where alluvium covers the limestone. Swallow holes are prominent in the outcropping Tindall Limestone and as such a high proportion of recharge via these swallow holes may be expected (Tickell 2005).

In the Katherine area where the Tindall Limestone outcrops the estimated average recharge is 100mm/year (Jolly 2002). In locations where the Limestone is overlain by Cretaceous aged clay and sand the average recharge has been estimated to be 50mm/year (Jolly 2002). In the unconfined aquifer the annual groundwater rises in wetter years are typically about 7m whereas in the areas confined by Cretaceous cover the rise in wetter years is about 3m (an example of these groundwater rises is shown in Figure 9). From Figure 9 it is apparent that rises due to annual recharge are more pronounced in the unconfined areas whilst being more muted in areas confined by the Cretaceous sediments (Jolly 2002). This is indicative of the lower recharge occurring. The longer term water level variations in Figure 9 are caused by long term rainfall changes.
Groundwater being influenced by gravity moves from recharge areas high up in the catchment towards low-lying discharge points. In the Katherine region the majority of these discharge points typically occur where the Katherine River intersect the aquifer. This discharge either occurs at distinct karstic springs or through seepage into streambeds (Tickell 2005).

The karstic springs of the Katherine region are distinctive features where water is discharged from solution cavities in the Tindall limestone (Tickell 2005). The water temperature is typically about 32°C, the same as the ambient groundwater temperature. In an area where dry season morning air temperatures may reach 10°C these springs are often referred to as “hot” or “thermal” springs and are of prime importance to tourism. The other mechanism by which groundwater discharges from the Tindall aquifer which is streambed seepage is actually the dominant form of discharge and is measured by comparing stream flow measurements along the river. The measured spring flows along the Katherine River only account for approximately 20% of the total discharge from the aquifer into the river.

Changes in the height of the water table can cause the extent of groundwater discharge zones to expand or contract (Tickell 2005). Elevated water tables as a result of above average rainfall periods are a good indication of this as they often cause groundwater discharge to occur in typically dry areas. This occurred in the Tindal area during the 2003/04 wet season when several large, localised rainfall events quickly filled the aquifer to such levels that discharge occurred over large areas where discharge had never been recorded. The groundwater was discharged through the karstic swallow holes that normally act as recharge points (see Figure 4). In an area of land off Zimmin Drive, shown in Figure 10, a small groundwater fed lake was formed in a shallow closed depression. These groundwater discharge zones dried up during the dry season with flow ceasing in the lowest lying area near Tindall Creek by September.

Figure 9  Comparison of groundwater levels in the unconfined Tindall aquifer (RN029429) and in the Tindall aquifer confined by Cretaceous sediments (RN022006) (Tickell 2005)
At the start of the dry season surface water runoff still dominates the flow in the Katherine River (Tickell 2005). However due to the cessation of the wet season rains this source does not last long and very quickly groundwater becomes the dominant component and by July typically all river flow comes from groundwater. This can be seen by analyzing both the river flow recession curves and the water chemistry. When the river flow is still high at the start of the dry season the electrical conductivity (EC) of the river water is low. The river flow then starts to decrease rapidly as surface runoff dissipates and subsequently the proportion of water from groundwater in the river increases resulting in a rise in EC. When surface runoff ceases this is marked in the recession curve of the river flow by an inflection point, typically at this time the EC of the water approaches the levels of the regional groundwater.

Longer term rainfall variations over multiple years as experienced in the region results in a similar variation in the groundwater discharge. Sequential above average wet season rainfalls has a significant impact on recharge and subsequently on the dry season river flows as shown in Figure 11.
Groundwater discharge to the Katherine River is currently at a high level in comparison to the historic record. Jolly et al (2000) determined a relationship between rainfall and recharge to the Tindall aquifer and calculated annual recharge rates for Katherine from 1888 to 1999 (see Figure 12). Their work identified that groundwater recharge (and hence discharge) has been considerably less than in recent times for significant periods during that time.
2.6 REGIONAL WATER BALANCE

A water balance is a tool that is used to summarize knowledge pertaining to rainfall, recharge and discharge data for an area. More simply it is a summary of what is currently known about the inflows and outflows of water within a catchment whilst taking into account any temporary storage of water that may occur (Jolly 2002). The components of the water balance as they apply to the Sculpture Cave catchment is summarized in Tables 1 and 2.

Table 1 Components of a Water Balance (Jolly 2002)

<table>
<thead>
<tr>
<th>Inflow</th>
<th>Outflow</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>Runoff</td>
<td>Reservoir storage</td>
</tr>
<tr>
<td>Inflows from adjacent groundwater resources</td>
<td>Evaporation and Transpiration</td>
<td>Water stored above and below the water table</td>
</tr>
<tr>
<td></td>
<td>Pumping</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Water Balance for the Katherine Area (Jolly 2002)

<table>
<thead>
<tr>
<th>Components of Water Balance</th>
<th>Annual Amounts for Catchment (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>Rainfall (DR014902, period 1957 – 2000)</td>
<td>500</td>
</tr>
<tr>
<td>Runoff (G8140001, period 1957 – 2000)</td>
<td>50</td>
</tr>
<tr>
<td>Recharge (period 1957 – 2000)</td>
<td>0</td>
</tr>
<tr>
<td>Transpiration by large trees</td>
<td>150</td>
</tr>
<tr>
<td>Understorey Evapotranspiration</td>
<td>300</td>
</tr>
<tr>
<td>Inflow from adjacent aquifers</td>
<td></td>
</tr>
<tr>
<td>Water stored above and below water table</td>
<td>6500</td>
</tr>
<tr>
<td>Pumping for water supply purposes</td>
<td></td>
</tr>
</tbody>
</table>

In the Katherine area the main hydrologic characteristic is the immense variability in the rainfall from year to year, within a single year and over periods of years. The variability in the rainfall results in similar variability in both the surface water runoff and groundwater recharge.

The period of record for most gauging stations and groundwater monitoring points within the region are biased towards a period of above average rainfall when compared to the long term rainfall record. This must be taken into account when analyzing flow and recharge data (Jolly 2002).
2.7 WATER ALLOCATION PLAN FOR THE TINDALL LIMESTONE AQUIFER (KATHERINE)

The following is a summary of the published WAP as relevant to the study (NRETAS 2009).

The development of a water allocation plan (WAP) for a region is important when there becomes serious competition for a water resource. This is as the water needs of a growing community with its expanding agriculture and industry should not impact upon the ecological and cultural values of that water resource.

The unconfined Tindall Limestone aquifer that is targeted by this WAP as shown in Figure 13 is one of the NT’s highest yielding sources of good quality groundwater. The water from this aquifer is important to the people of the region as it supplies drinking water to the town of Katherine and the Tindal RAAF Base as well as many rural properties via their own private bores. The other large users of groundwater from the Tindall aquifer are agriculture and industry which both significantly boost the local economy.

The local community which includes the Jawoyn, Wardaman and Dagoman peoples have indicated that the features of the aquifer have a high cultural value. These peoples have a deep seated spiritual connection with the billabongs, swamps, rockholes, sinkholes, springs and rivers that are associated with the Tindall aquifer.

Water from the Tindall aquifer makes its way into the Katherine River by upwelling through the riverbed and discharging from springs like the Katherine Hot Springs. This discharge from the Tindall aquifer permits the Katherine River to continue flowing throughout the dry season. The WAP contains provisions to ensure the perennial nature of the Katherine River is maintained by managing the Tindall aquifer discharge.

The WAP having been officially declared by the Federal Minister for Natural Resources, Environment and Heritage, on the 19th August 2009 has a lifespan of 10 years and will undergo a review in 5 years. The review ensures that the WAP can stay relevant and effective by incorporating any new knowledge that may have since been gained.

The provisions of the WAP are such that they represent a tradeoff between consumptive water uses and environmental flows. These provisions are there to protect the flows in the Katherine River and so that the recommended environmental flow requirements for the Daly River (which is downstream) are met. The provisions were developed by taking into account the demand for water in the WAP area, the recommendations made by Erskine et al (2004) and the recommendations made by the Katherine Water Advisory Committee (KWAC) in particular about the acceptable reliability conditions for extraction licences.

Measures have been taken to safeguard environment flows in the WAP. An example of this is when the late dry season flows in the Katherine River are predicted to be less than 0.6 cumecs then 87% of the annual Tindal aquifer discharge is preserved for environmental flows. The remaining 13% of annual discharge is allowed to be extracted. Note that this figure is equivalent to the estimated volume of water used by the public water supply, unlicenced rural stock bores, domestic bores and
other small volume groundwater users. This means that licenced extractions for agriculture, aquaculture and industry would be in effect reduced to zero when this low flow threshold is reached. This low flow threshold of 0.6 cumecs is the 90th percentile minimum flow in the Katherine River near the Katherine Railway Bridge which means that for 90% of the years this flow is exceeded.

Figure 13 Area covered by the Water Allocation Plan
3 FIELD SITE AND METHODS

3.1 SCULPTURE CAVE GAUGING STATION

3.1.1 G8140025 HISTORY

The gauging station (G8140025) at Sculpture Cave was constructed for the wet season of 1996/97 to quantify the amount of water flowing into the cave. This initial deployment consisted of an Acoustic Doppler Current Profiler (ADCP) being installed at the entrance to the cave. This is shown in Figure 14.

![Image of Starflow ADCP mounted in front of Sculpture Cave](Photo: S. Lawrie)

The trial of the ADCP in 1996/97 indicated there was sizable flow into the cave and in the year 2000 the decision was made to permanently equip G8140025. A Starflow ADCP was then deployed at the site for the subsequent wet seasons. The ADCP deployment successfully collected data for the first three wet seasons of 2000/01, 2001/02 and 2002/03. In subsequent wet seasons no data was obtained as the ADCP was plagued with issues ranging from data retrieval errors, battery issues and fire damage resulting in the closing down of G8140025 in 2006.
As part of the operations at G8140025 two automatic rainfall stations were installed within the gauging station’s catchment. These rainfall stations (R8140002 and R8140003) successfully collected data for the duration of the ADCP deployments. Also in operation during the ADCP deployments were groundwater level loggers in monitoring bores both up gradient (RN008221) and down gradient (RN029429) of the cave. These water level loggers were part of a larger regional groundwater monitoring program. The location of these sites is shown in Figure 15 with a sample of the data they collected for the wet season of 2002/03 being shown in Figure 16.
3.1.2 PRINCIPLES OF ADCP OPERATION

The ADCP is a major technological breakthrough that has proven itself very useful in the Water Resources field. It can be used in very challenging and extreme environments, like the study area. ADCP’s can either be downward-looking like the ones used to gauge rivers from boats or they can be upward-looking and mounted permanently on a streambed. In this study an upward-looking Starflow ADCP on a fixed bottom mount (see Figure 14) was used as it would be unattended for the duration of the wet season and only be sporadically inundated with variable amounts of water.

An ADCP works by emitting acoustic waves through the water column (Wall, Nystrom & Litten 2006). In the water there are suspended particles which are assumed to be moving at the same speed as the water. The acoustic waves hit these particles and return an echo of which the frequency and amplitude are recorded by the ADCP. If these particles are moving then they cause a Doppler (frequency) shift in the returned echo. The ADCP uses this to calculate the particle velocity which is assumed to be the same as the water velocity. The transducers in the ADCP generate multiple acoustic beams and the ADCP records the velocities from a series of bins that make up each beam, a schematic of which is shown in Figure 17. Using the Doppler shift in each bin and beam the ADCP can calculate velocity vectors for the water column (Wall, Nystrom & Litten 2006).

Figure 17 Schematic diagram of upward-looking ADCP (Wall, Nystrom & Litten 2006)

Figure 18 Sculpture Cave cross-sectional area at the ADCP site
The ADCP measures both the velocity and stage height of the water column. Using the surveyed cross section of the site, see Figure 18, the channel cross-sectional area can be calculated for any given stage height. This channel area is then multiplied by the stream velocity at that point in time to generate a flow value. This method is used to calculate a continuous flow record which in the case of Sculpture Cave would correspond to an individual flow event. These calculations were undertaken by the experienced hydrographic staff of NRETAS who were responsible for the operation of the gauging station.

### 3.1.3 PRELIMINARY ANALYSIS OF ADCP DATA

A preliminary analysis of the ADCP data in January 2009 showed that whilst the ADCP worked and was able to collect flow data the meaningfulness of this data was questionable. The technical report documenting the analysis of the ADCP deployments in more detail is included in Appendix C. The flow data for the events shown in Figure 19 highlight the irregularity of the data in that it does not appear to show the entire flow record at the site with the flow apparently starting and stopping with an unnatural regularity. Upon visitation to the site it was found that the rock base the ADCP was mounted on contained voids some 2-3m deep that would easily facilitate the passage of water. It was determined that there may indeed be a significant portion of flow that the ADCP does not register.

The analysis mentioned above also made a comparison of the catchment runoff and the measured cave inflow, shown in Figure 20. The estimated catchment runoff was obtained by using data obtained from the McAdden Creek gauging station (G8140158). G8140158 is 15km NNE of Katherine and receives minimal groundwater input. This makes the flow data obtained from this gauging station for all practical purposes analogous to the runoff off the catchment. The rainfall characteristics over this small area of the Katherine region were shown to be very similar and as such the Sculpture Cave recharge area should be able to be characterized by the runoff from G8140158. The runoff data from the G8140158 catchment (in millimeters) can then be used to determine the expected runoff from the Sculpture Cave catchment which has an area of 42 square kilometers. The comparison of the estimated runoff and the measured cave inflow in Figure 20 indicates that the ADCP measured flow only represents a fraction of the estimated catchment runoff.
3.2 FIELDWORK

3.2.1 FIELDWORK OVERVIEW

The aim of the work undertaken in this study was to try to understand and obtain something meaningful from the data collected from the ADCP deployments.

Upon the first site visit to G8140025 in early January 2009 it was noted that the landscape of the cave entrance provided what initially seems like an ideal location to install an ADCP. However upon further investigation it was found that the ADCP was installed on a rock mound which contained cavernous voids some 2.2m deep which could accommodate significant throughflow. It was decided that a water level logger should be installed in this void to clarify the intermittent flow record (see Figure 19) at this site. In a subsequent field trip in late January 2009 two water level loggers were installed in this void at the site.

The flow into Sculpture Cave is of a significant magnitude, however there was no visual record of the flow. This is as access to the cave during flow events is hazardous due to the size of the flow events and the unpredictability of the karst terrain. It was decided that a visual record of the flow should be obtained. A time lapse camera was installed on the gauging station instrumentation box located on higher ground overlooking the entrance to Sculpture Cave. This time lapse camera was triggered by flow events through water probes that were placed in the same void as the water level loggers.
Figure 21  Wet season vegetation cover in front of the entrance to Sculpture Cave

During the earlier site visits which occurred in January at the start of the 2008/09 wet season there was significant vegetation cover at the site and the surrounding area, see Figure 21. This hampered any attempt to conduct a thorough field inspection of the site and the surrounding region. However in the subsequent site visits to retrieve the equipment at the cave the vegetation cover was significantly reduced. This was due to these visits occurring in August 2009 in the middle of the dry season. The increased ground visibility enabled a thorough field inspection to take place. This field inspection resulted in the identification of several swallow holes in close proximity to the cave. The decision was then made to undertake a level survey in order to level in these swallow holes in relation to the ADCP level.

3.2.2 WATER LEVEL LOGGER INSTALLATION

The water level loggers used in this study were MiniDivers. This particular model of logger is a sealed unit and has a non-replaceable battery. In previous deployments by the Department these loggers have been shown to be unreliable with failures in the field having been experienced on a number of occasions. The decision was made to utilize two loggers at the site in the case that one of them failed. These loggers were suspended at depths of 2.1m and 2.2m from the top of a drilled PVC pipe mounted in a 2.2m deep cavernous void adjacent to the ADCP mounting, the installation is shown in Figure 22.
3.2.3 TIME-LAPSE CAMERA INSTALLATION

The gauging station at Sculpture Cave consisted of the ADCP mounted at the cave entrance with the power source for the ADCP being located in a gauging station instrumentation box located on higher ground overlooking the cave entrance. The solar panel from the ADCP deployments still remained at the site. This solar panel was utilized in conjunction with a wet cell battery to provide a power source for a time lapse camera.

The time lapse camera was constructed from consumer grade electronics by Paul Peng, an electrical engineering student undertaking vacation work at NRETAS. The construction method of the camera is deemed outside of the scope of this study but has been fully documented (Peng 2009).

The time lapse camera was mounted on top of the gauging station instrumentation box adjacent to the solar panel. This provided a good field of view over the cave entrance as shown by a sample photograph in Figure 23. The time lapse camera was triggered by water-sensitive probes which were mounted in a PVC pipe adjacent to the water level loggers at the cave entrance.
The camera was set to a 5 megapixel resolution and the storage made available to it was a 16 gigabyte memory card. At this resolution the images would have a maximum size of 2.5 megabytes providing enough storage for approximately 6400 images. The time lapse between photographs was set to approximately 15 minutes. If the camera were to shoot continuously there would be enough storage for over 2 months which would cover the time period when most of the runoff is expected to occur (February to March).

3.2.4 FIELD INSPECTION

A field inspection was undertaken during a site visit to retrieve data from the deployed equipment. This field inspection occurred at the end of the dry season in August 2009 and was undertaken with an experienced hydrogeologist, Peter Jolly. The purpose of the field inspection was to identify possible causes for the low ADCP flow measurements. The first steps involved were examining the structure of the cave entrance. The field inspection then spread into the region surrounding the cave, focusing on the areas on the upstream side of the cave. Attention was paid to any possible surface connections to the karstic conduits below, typically in the form of swallow holes, see Figure 24. The inspection also looked for any signs of flood debris such as grass and leaves lodged on tree trunks and fences, an example of this at the site is shown in Figure 25.
Figure 24  Swallow hole near Sculpture Cave

Figure 25  Flood debris in the form of grasses lodged on a fallen tree
As a result of the field inspection it was decided that a level survey would be required. This was in part because the elevations, in the form of 2m contours, from the existing topographic map were of insufficient detail. The aim of the level survey was to level in the swallow holes in the region near the cave entrance. The main reason for this was that it was suspected that the points at which water can enter these swallow holes were low enough that runoff from the catchment could enter these swallow holes before it entered Sculpture Cave. A level survey was undertaken in September 2009, see Figure 26. The equipment used in this study was composed of a level and a leveling staff and the leveling procedures used were identical to those published by dela Cruz (1983). The following is a summary of dela Cruz's surveying technique that was used in this level survey.

Horizontal distances in the survey were measured by the stadia method and crosschecked using the pacing method. The stadia method can be used when the telescope in the level instrument has stadia hairs.

The horizontal distance can be determined by obtaining staff readings for the upper and lower stadia hairs of the level as shown in Figure 27.
The formula for the level used in the survey for calculating the horizontal distance is:

\[ \text{Horizontal Distance} = (\text{Upper staff reading} - \text{Lower staff reading}) \times 100 \]

However there were times in the survey when either an upper or lower staff reading was unable to be taken. In these situations a modified distance formula was used:

\[ \text{Horizontal Distance} = (\text{Upper or lower staff reading} - \text{Middle staff reading}) \times 2 \times 100 \]

The pacing method consists of pacing the distance between readings with a pace being defined as the length of a normal step of an individual. This method provides an accuracy of roughly 0.6m in 30m. The pacing method was used in this study to verify the stadia distance measurements.

The measurement of distance in the vertical plane was achieved by using the standard leveling technique which is outlined below where the changes in height corresponded to the middle staff reading. If the two points to be leveled are visible from the level as in Figure 28 then the difference in elevation is given by:

\[ H = H_a + H_b \]

![Figure 28 Leveling technique when the two points are visible from level (dela Cruz 1983)](image)

In the case of Figure 28 if the elevation of point A, EL_A, is known then the elevation of point B, EL_B, can be determined. In leveling terminology the reading H_a is known as a backsight (BS) as the elevation is known and the reading H_b would be known as a foresight (FS) because the elevation is unknown. The process of finding the elevation of point B is as follows:

\[ \text{EL}_B = \text{EL}_A + \text{H}_a - \text{H}_b \]

\[ \text{EL}_B = \text{EL}_A + \text{BS} - \text{FS} \]

If as in Figure 29 the points to be leveled are not visible from each other, as was the case for this survey, then a series of differential leveling takes place. This essentially iterates the simple process shown above by leveling in a series of changepoints (TP) until the objective point is visible from the level.
This survey was brought in from the boundary fence down along the defined channel bed to the ADCP mounting plate as shown in Figure 30. During this survey several cross-sectional transects of the channel bed were also taken on the approach to the cave, as well as the levels of the lips/edges of a number of swallow holes and flood debris. The survey was then closed by leveling from the end point to the starting point.

There existed no reasonable AHD benchmarks within close proximity to Sculpture Cave with the only one in the Nature Park Reserve being of considerable distance away. It was decided that for the purpose of this study detailed elevation data was not strictly necessary. The reference point used to start this survey was the intersection of the track and the fenceline as shown in figure 18. The
elevation of this reference point, 145m AHD, was obtained from Google Earth and this elevation was used to determine the reduced levels for the survey.

The survey was started at dawn and finished at midday. The early start was necessary to avoid issues relating to heat haze which in the Tropics becomes significant during the middle of the day. Issues relating to heat haze were experienced towards the end of the survey as the time approached midday. This resulted in difficulties in reading the levels on the staff.

3.3 DESKTOP STUDY

3.3.1 RECHARGE ANALYSIS

Field work identified that the aim of this project could not be met with the existing data. The existing data was insufficient to model the recharge occurring at Sculpture Cave.

Jolly et al (2000) reported on a method they developed to determine the recharge to the Tindall Limestone aquifer in the Katherine area. As the data obtained from the ADCP did not provide the information required to compute recharge in the Sculpture Cave area, it was decided to investigate the potential for using the recharge values calculated by Jolly et al (2000) to estimate recharge in the Sculpture Cave area. Jolly et al. (2000) used their recharge data to synthesise spring flows from the Tindall Limestone aquifer into the Katherine River between 1885 and 1999. The synthesis was based on an analysis of Katherine daily rainfall records that have been recorded since 1873 and dry season baseflows measured in the Katherine River since 1954. This analysis indicated that these groundwater fed flows range between a low of approximately 0.65 cumecs (in 1930 and 1966), and a high of about 3 cumecs (around 1900 and 1980). A plot of these synthesised groundwater flows is shown in Figure 31.

![Synthesised groundwater fed flows from the regional Tindall Limestone Aquifer into the Katherine River at Galloping Jacks, GS8140301 (Jolly et al. 2000)](image-url)
Since the completion of that report the water year rainfall (October to September) in the Katherine region has been extremely high. The long term mean annual rainfall for Katherine is 980mm. In the decade since 1996 the mean water year rainfalls for Katherine has been 1240mm. The impact and significance of this increase in rainfall can be determined from the relationship between potential recharge and water year rainfall for Katherine derived by Jolly et al (2000) which is shown in Figure 32.

The relationship shown in Figure 32 shows that the estimated water year recharge for a rainfall of 980mm is 250mm whilst for a rainfall of 1240mm the estimated recharge is 440mm. This means that an increase of 26% in the water year rainfall will result in a 76% increase in the estimated recharge.

Jolly et al (2000) estimated recharge from the daily rainfall record, using estimates for the end of dry season soil moisture deficit and daily losses (evapotranspiration etc). It was assumed that there was little surface runoff from the ground overlying the aquifer in the Tindall Limestone. This assumption is based on the precept that the majority of overland flow above sub-cropping Tindall Limestone eventually recharges the aquifer via diffuse recharge and swallow holes. From the field inspection undertaken as part of this study this assumption appears to be valid for the area in the vicinity of Sculpture Cave.

Since 1996 groundwater levels in the vicinity of Sculpture Cave appear to have been maintained at a high level, as shown in the water level plot for bore RN029429 shown in Figure 33. This supports the earlier assertion that recharge has been significantly higher in recent times.
As most of the irrigation development has taken place in Katherine since 1996 (verbal advice Anthony Knapton), there may be the expectation in the community that these high rainfalls are the “norm”. Sustainable development of a water resource requires a sound understanding of the long term behaviour of the resource. This is particularly the case with reaches of perennial rivers where there is strong interaction between the river and the groundwater resource that sustains flows in the river during dry periods. The Katherine River is a good example of such a river.

The main hydrologic characteristic of the region that impacts on recharge has been identified to be the great variability in rainfall within a single year (see Figure 33), from year to year (see Figure 34) and over periods of years (see Figure 35).
It was noted that the period of record for most gauging stations (since the 1960’s) and groundwater monitoring points (since the 1970’s) within the Katherine River catchment is biased towards a period of above average rainfall as shown in Figure 35.

To enable data acquired on groundwater to be appropriately utilised for Water Allocation Planning purposes, it was determined that a statistical analysis of the rainfall data was required.
The objective therefore of the analysis undertaken was to determine how representative the Katherine rainfall record was of probable long term trends in rainfall so that the data can be used to inform the assessment of the risks associated with using the current limited hydrological data sets. This was achieved by undertaking a Monte Carlo simulation of annual rainfall.

### 3.3.2 RAINFALL ANALYSIS

#### 3.3.2.1 ANALYSIS OF EXISTING RAINFALL INFORMATION AND PAEOLCLIMATE DATA

The Katherine region has consistent rainfall data extending back to 1888, see Figure 34 and Appendix A. For the period from 1888 to 1984 daily rainfall data was acquired by staff who manned the Katherine Post Office. The rainfall station at the Post Office is DR014902. Over this extensive period rainfall data is not available for only 4 months. Data from nearby rainfall stations DR014904 and DR014923 were used to fill these gaps (see Appendix A for data and Figure 36 for location of rainfall stations).

Unfortunately since 1984 daily rainfall data has not been consistently collected at this site. Therefore another site close to DR14902 needed to be chosen to extend the data from 1984 to present. Initially it was thought that the rainfall data collected at the nearest rainfall station at river gauging station G8140001 could be used. However on inspection of the site it was determined that the rainfall collection technique was non-standard and may bias the analysis of the long term record. Rainfall at the site is collected via an instrument located on top of the river gauging station shed. When rainfall data recorded by G8140001 was plotted against that obtained from another nearby rainfall station, DR014903 that used a standard rain gauge there appeared to be a trend of under recording, see Appendix B.

![Figure 36 Location of Rainfall stations referred to in this report (Source: NRETAS HYDSTRA Database)](image-url)
In papers prepared by the Bureau of Meteorology (1997) and Curtis (1996) it has been noted that measured rainfall decreases as the height of the gauge orifice above the ground increases. In this instance the under recording appears to be of the order of 5%. Hence another site, DR014910 was chosen that used the same collection technique as was used at DR14902. However over the period since 1984 this station is missing 25 months of data. These gaps were infilled by data from nearby rainfall station DR014903.

A number of studies of paleoclimate across northern Australia have identified that a similar climate to the present has existed for the past 8000 years with extended periods that were slightly wetter or dryer (Adams et al 1997). The data from these studies is consistent with trends found elsewhere in Australia and in many other countries around the world. Therefore this study focused on developing a statistically valid rainfall record for Katherine for a period of 8000 years during which rainfall patterns are believed to be similar to those that have occurred since 1888.

### 3.3.2.2 MONTE CARLO SIMULATION

Computer simulation involves using computer models to imitate real life and/or make predictions. The typical type of model used has a certain number of input parameters that are mapped by a set of equations resulting in a set of outputs. This type of model is deterministic in that the same results occur regardless of how many times the model is recalculated (see Figure 37).

![Figure 37](image)

**Figure 37** Input variables $(x_1, x_2, x_3)$ mapped by a parametric deterministic model $(f(x))$ to a set of output variables $(y_1, y_2)$.

The Monte Carlo simulation is a method for iteratively calculating a deterministic model using sets of random variables as inputs (ENVE2605 2007). This method is often used when the model is complex, nonlinear or involves more than a few uncertain parameters. A simulation can typically involve over 10,000 evaluations of the model which is a task that in the past was only practical using super computers.

The simulation works by using a random percentage variable as an input to an inverse cumulative-probability function (ENVE2605 2007). Firstly, a random probability variable, $n$, is generated. This probability, $n$, along with the mean and standard deviation of the sample distribution is then used in Excel’s NORMINV function to generate a predicted value for that event. Excel’s NORMINV function works by evaluating the quantile function for the normal distribution. It does this by returning the $n^{th}$ percentile of a normal random variable with mean, $\mu$ and standard deviation, $\sigma$. This process is repeated as required until a suitable sized random dataset is obtained. The distribution of this dataset can be classified as normal, and it will be distributed like the normal distribution shown in Figure 38, where 68% of the data will lie within one standard deviation from the mean ($\pm 1\sigma$), 95% will be within $\pm 2\sigma$ and 99.7% will be within $\pm 3\sigma$ from the mean, $\mu$. 
The resulting dataset will conform to the probability density function of the normal distribution:

\[
f(x; \mu, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]

The distribution of the Katherine annual water year rainfall (September to October) can be considered normal for all intensive purposes as shown in Figure 39. Hence, we do not need to use the other models such as lognormal and log-Pearson. Furthermore Edwards, Classen and Schroten from the Food and Agriculture Organization of the United Nations (1983) have shown that for areas with decent annual rainfall data the normal distribution is sufficient. This is also supported by the normal shape of the actual rainfall distribution from the 119 years of record for Katherine. Using this information a fairly accurate theoretical model of the situation is able to be made.

From the historical data we are able to determine that the mean, \( \mu \), of Katherine's rainfall is 986mm and the standard deviation, \( \sigma \), is 281.7mm. It has also been shown by Srikanthan et al (2002) that there is no two state persistence in the Katherine region, i.e. that the climate there is not composed of two states, either a dry state (low rainfall year) or a wet state (high rainfall year). Thus the rainfall is best presented by a single state model with no persistence. Using this information we are able to utilise the Monte Carlo simulation to produce 8000 years of randomly generated, normally distributed simulated annual rainfall data.
New simulated rainfall data is generated every time new random numbers are generated when the spreadsheet is recalculated. An example of the data is shown in Figure 40 and the distribution of that data is shown in Figure 41.

**Figure 40** A single Monte Carlo simulation run of 8000 years of rainfall data for Katherine

**Figure 41** Distribution for a single Monte Carlo simulation run of 8000 years of rainfall data for Katherine
4. RESULTS

4.1 WATER LEVEL LOGGERS

Two water level loggers were installed at the site for redundancy purposes. This strategy proved vital as one of the loggers actually failed in the field. These equipment failures had been experienced by NRETAS personnel on previous occasions when using MiniDiver loggers. This has prompted a change in operating procedure when using this particular logger whereby it necessitates the installation of simultaneous loggers at water level monitoring sites. The water level data, corrected to the ADCP level, from the logger that remained operational during the deployment is shown in Figure 42.

![Figure 42](image)

**Figure 42** Water level data (corrected to ADCP level) from logger installed at the ADCP site at Sculpture Cave.

The water level loggers were installed before any significant surface runoff event had taken place in the area, as shown by the photographs from the cave in Figure 43. The time-lapse camera was installed before the second and third flow events. Photographs by Paul Peng from the site visit to install the camera system, see Figure 44, show the impact of the first significant flow event of the season.
Figure 43  Inwards and outwards views from the cave entrance before the first flow event of the wet season as recorded by the logger (Photo: P. Peng).

Figure 44  Inwards and outwards views from the cave entrance after the first flow event of the wet season as recorded by the logger (Photo: P. Peng).
The camera deployment from February to August 2009 yielded over 6 gigabytes of photographs. There were 234 flow related images, capturing two distinct flow events. The deployment of the camera was too late to capture the first flow event of the season. There were also approximately 50 images that although not pertinent to this study were of interest due to their containing photographic evidence of wildlife at the site.

The camera having been deployed two weeks after the water level loggers was able to capture images of the last two flow events as recorded by the water level logger (see Figure 42). A selection of captured flow images are shown in Figure 45 and Figure 46.

**Figure 45** Successive time lapse images from 4:58AM and 5:15AM on the 15/02/2009 showing movement of flood debris towards the cave

**Figure 46** Successive time lapse images from 6:35AM and 6:52AM on the 15/02/2009 showing the water level rising at the cave.
Figure 47  Time lapse image from 1:26PM on the 19/08/2009 showing an agile wallaby (lower right hand corner) drinking from the perched water table of the cave system.

The fauna movement captured by the camera indicated diversity within the area. The perched water table in the cave system enabled year round access to water in an environment that by the end of the dry season is water scarce. An agile wallaby having a drink from the cave in the late dry season is shown in Figure 47. In addition to the presence of a significant number of agile wallabies (*Macropus agilis*) there were also other types of animals visible in the time-lapse photographs of the cave entrance. These included goannas (*Varanus* spp.), native doves (*Geopelia* spp.), Blue-winged Kookaburras (*Dacelo leachii*), a Torresian Crow (*Corvus orru*) and a Little Pied Cormorant (*Phalacrocorax melanoleucos*).
4.3 FIELD INSPECTION

The field inspection of the site found that there were many avenues for water to enter the subsurface before it reached the cave. Numerous swallow holes were found in the immediate vicinity, some of which are shown in the Figure 48 and Figure 49. These ranged in size between man-sized cave entrances and holes just big enough for a horse’s hoof and had depths of up to 4m below ground level. Through each of these openings the karstic conduit channels which facilitate the flow of water in the subsurface were clearly visible and of significant size. In addition to these clearly visible swallow holes a number of major sinkhole depressions were found. The floors of these sinkhole depressions were not visible (see Figure 48 - picture 2) due to the amount of leaves and debris accumulated in them. However it is highly likely in this terrain that somewhere on the depression floor these sinkholes have an opening/s to the subsurface karstic conduits. There existed a real danger of falling down one of these hidden openings when walking over these sinkhole depressions like the author is doing in Figure 48.

The field inspection also identified flood debris remaining from the surface flow events from the previous wet season. The flood debris is shown in Figure 25 and being leveled in Figure 51.

![Figure 48](image1) Swallow hole (picture 1) and sinkhole (picture 2) near Sculpture Cave

![Figure 49](image2) Swallow holes near Sculpture Cave
4.3 LEVEL SURVEY

The results of the level survey are shown in Figure 50 with levels adjacent to blue marks indicating level of the lip of a swallow hole.

![Figure 50](image)

**Figure 50** Relative levels as determined by the level survey with swallow holes marked in blue.

Flood debris was identified and leveled in as shown in Figure 51. The level of this flood debris indicated that the flow event that left the debris exceeded the bankful capacity of the defined streambed.

![Figure 51](image)

**Figure 51** Leveling in flood debris (144.1m RL).
In the exploration of the countryside that occurred during the level survey it was found that when the surface runoff exceeds the swallowing capacity of the swallow holes in this area it then flows out of the region the catchment. This “bypass” flow as seen on Google Earth then continues down Tindal Creek which then possibly flows into other swallow holes as it flows northwest towards the Katherine River (see Figure 52).

Figure 52  Sculpture Cave Catchment showing the route of “bypass” flow down Tindal Creek.
4.4 MONTE CARLO SIMULATION RESULTS

It was determined that the best technique that could be used to present the 8000 years of simulated annual rainfall data so that trends could be visually determined was the use of annual rainfall mass residual curves. To prepare a rainfall mass residual curve a long period of rainfall data is obtained so that the long term average rainfall can be derived. For the period examined the recorded rainfall value for the year is subtracted from the mean and the result for each year is called a residual.

The residual values over time are added and graphed against time to produce the rainfall mass residual curve. Where the slope of the curve is increasing, during that period rainfall exceeds the long term average meaning wetter periods. Where the slope of the curve is decreasing, during that period rainfall is less than long term average meaning generally drier periods.

When the residual mass curves are plotted for the simulated rainfall data for 8000 years it became apparent that the data always contained some notable trends. When looking at the cumulative sum from the mean there are noticeable “wet” and “dry” spells that can occur for many hundreds of years as shown in Figure 53.

![Graph of rainfall mass residual curves](image)

**Figure 53** Examples of "Wet" and "Dry" periods in residual mass curves for 8000 years of rainfall data for Katherine.

Analysis of the data for five wet and five dry spells each lasting at least 400 years were chosen and analysed. The percentiles of each period were calculated. This was then averaged for both the wet and the dry spells. A comparison of these to the normal distribution is shown in Figure 54. For the five
wet and five dry spells analysed, the dry spell is caused by a decrease in the mean by only 35mm on average, similarly the wet spell is caused by an increase in the mean by an average of 35mm. As visible in the distribution of the percentiles these spells are only caused by a change in the mean and not in the shape of the distribution of the rainfall, i.e. they are not caused by an increase in occurrence of extreme rainfall events.

The analysis as shown in Figure 54 also indicated that the existing 119 year rainfall record for Katherine (see Appendix A) is representative of the probable long term variation in rainfall as simulated. However the 66 year period from 1899 to 1965 and the 40 year period from 1966 to 2006 are not representative of the probable long term variation in rainfall as simulated.

Further analysis of the data was done to determine the significance of the very much above average rainfall that has occurred in Katherine over the 10 year period from 1996/97 to 2005/06. This was achieved by analysing the simulated 8000 years of rainfall data to determine percentiles for the 10 year running mean for the simulated data and determining the percentile for the 10 year running means from 1888 to 2006 (see Figure 55). Further analysis indicates that the mean rainfall of 1240mm for the 10 year period from 1996/97 to 2005/2006 lies at approximately the 99.7th percentile (see Figure 56).
Figure 55  Ten year running mean percentiles for simulated data and full period of Katherine rainfall record.

Figure 56  Ten year running mean for simulated data and full period of Katherine rainfall record for highest 1 percentile.
4.5 MODELED RECHARGE ESTIMATES

Jolly et al (2000) estimated potential recharge from the daily rainfall record, using estimates for the end of dry season soil moisture deficit and daily losses (evapotranspiration etc). They assumed that there was little surface runoff from the ground overlying the aquifer in the Tindall Limestone. This assumption was based on the assumption that the majority of overland flow above sub-cropping Tindall Limestone eventually recharges the aquifer.

It was noted, however, that surface runoff was included in the figure derived for the potential recharge rate. Subsequent modelling work in the Daly Basin (Knapton (2006) has identified that of the potential recharge rate, where water levels do not rise above ground level during the wet season, approximately 60 percent will be surface runoff and 40 per cent recharge. Most of the 42 square kilometre catchment above the Sculpture Cave area is underlain by the Jinduckin Formation, a low permeability formation when compared to the Tindall Limestone. It may therefore be expected that approximately 60 percent of the potential recharge will also be surface runoff in this catchment.

Given the location, size and number of swallow holes in the Sculpture Cave area it would be expected that this assumption should be valid for average to drier than average water years but may overestimate recharge in wetter than average years. This observation is primarily based on the observation that there is a distinct drainage channel coming into the Sculpture Cave area from the 42 square kilometre catchment, but none leaving it. The drainage leaving the area is in the form of a broad shallow depression with no distinct drainage channel.

If it is assumed that all of the estimated annual recharge to the swallow holes in the Sculpture Cave area actually recharges the aquifer, then the water year recharge can be calculated by multiplying 60% of the potential water year recharge calculated by Jolly et al (2000) by the area of the catchment, 42 square kilometers. The estimated water year recharge (in megalitres) for each water year from 1888 to 1999 is plotted in Figure 57. The percentiles for the period are also given in Figure 58 with recharge values also being given in cumecs which equates to the average instantaneous recharge rate for the entire water year. The mean recharge rate for the period was equivalent to a rate of 0.19 cumecs, the median to a rate of 0.15 cumecs.

The mean recharge for the period is equivalent to a mean annual input of groundwater into the Katherine River that will maintain a flow of approximately 0.19 cumecs for the entire year. The synthesis of spring flow undertaken by Jolly et al (2000) indicated that the mean spring inflow into the Katherine River from the aquifer in the Tindall Limestone from 1884 to 1999 was approximately 1.2 cumecs (see Figure 31). Therefore recharge via swallow holes in the vicinity of Sculpture Cave may be contributing of the order of 15% of the spring inflow into the Katherine River over the period 1884 to 1999.

It is possible that a significant percentage of surface runoff may flow past the swallow holes in the vicinity of Sculpture Cave. However available data does not allow a determination of the percentage of the estimated recharge that will bypass the swallow holes in the vicinity of Sculpture Cave.
Figure 57  Modeled estimates of water year recharge to the swallow holes in the Sculpture Cave area.

Figure 58  Percentiles for modeled estimate of water year recharge to the swallow holes in the Sculpture Cave area.
5. DISCUSSION

5.1 SIGNIFICANCE OF SCULPTURE CAVE GAUGING STATION

Karst hydrogeology differs tremendously from typical groundwater hydrology and a lot of the techniques used in karst are borrowed from other disciplines (Goldscheider & Drew 2007). The deployment of an ADCP at Sculpture Cave is testament to the ever-developing methods in karst hydrogeology. The ADCP in 1997 was a device that was fast making inroads in the Water Resources field in particular with the application of river flow gauging which up until this point was an extremely hazardous task fraught with dangers. The budget of the Water Resources Division allowed a trial of using this now affordable technology in a karst groundwater setting. As with the application of any new technique in the field success was not guaranteed but a successful trial would only add to the growing list of methods in karst hydrogeology.

A karstic system has many inputs (diffuse recharge, point recharge) which with regards to point recharge is highly heterogeneous in nature, however the system culminates in typically only a few discharge points (springs). The typical approach to groundwater monitoring in a karst setting has traditionally focused on those spring outputs as it is probably the most cost effective monitoring technique (Goldscheider & Drew 2007). Efforts to analyse point recharge occurring via swallow holes in the region have traditionally been restricted to tracer tests (Karp 2005). Tracer tests are a cost effective method of mapping the hydraulic connectivity of the karstic conduits. They are most effective in assigning travel times from Point A to Point B which in a typical MODFLOW model would be significantly overestimated by orders of magnitude (see example in Figure 59) (Goldscheider & Drew 2007). Tracer tests for the most part remain qualitative in nature and do not provide information on the quantities of water involved (Goldscheider & Drew 2007).

![Figure 59](image.png)

*Figure 59* Example from Walkerton, Canada showing a MODFLOW predicted bore capture zone and actual field data for trajectories and travel times through the karst subsurface (Goldscheider & Drew 2007).

5.2 EVALUATION OF ADCP FLOW DATA

The ADCP installed at the Sculpture Cave gauging station successfully collected flow data for four wet seasons. During the operation of the gauging station in 1997/98 and from 2000 to 2006 a lot of time, effort and money was put into collecting data at this site, including the simultaneous operation of two associated rainfall stations. An initial analysis of the recorded ADCP flow data indicated that the
ADCP was only registering a small proportion of the flow that would be expected at the site. It was decided that further investigation was warranted to try and extract some meaningful data from the costly ADCP deployments.

It was found that the ADCP was installed on a rock base that contained voids up to 3m deep. The decision was made to install water level loggers in to these voids to determine if significant flow through them occurs. The water levels as recorded by the loggers installed in the voids adjacent to the ADCP installation location cleared up the behavior of the recorded ADCP flow. It indicated that there was significant throughflow occurring through the voids in the rock base the ADCP was mounted on which was not registered by the ADCP. This clarified parts of the ADCP record whereby a sequence of flow events in a short period of time would be registered (see Figure 19). When in fact the data from the water level logger clearly showed that these were part of a larger flow event of which a significant part was not registered by the ADCP. However even if the ADCP flow were adjusted to account for this unregistered flow it still would not account for the amount of expected inflow.

The field inspection of August 2009 revealed multiple swallow holes in the vicinity of Sculpture Cave. It is noted that the first preliminary field inspection at the site occurred in January of 2009. The wet season was already underway and the vegetation cover was significant, see Figure 21. During this visit a thorough field inspection was unable to be taken due to the reduced ground visibility. This reduced ground visibility also meant that there was a serious possibility of serious injury as many of the surface openings were not visible and could potentially lead to an unintended fall of up to 4m. The next fieldtrip undertaken by the author to retrieve the installed equipment at the site occurred in August in the middle of the dry season. At this point in time most of the vegetation had either died off or been ravaged by fire thus significantly increasing ground visibility. The result of this field inspection was the identification of several swallow holes in close proximity to Sculpture Cave and that further work was warranted in the form of a level survey.

The level survey found the relative levels of the ADCP at the cave entrance and the swallow holes in the immediate vicinity. It was found from this survey that the flow at the cave entrance would only be active after a fair amount of water has entered the system through the other swallow holes. This meant that the ADCP at its location at the cave entrance would not give a good indication of the amount of point recharge occurring in the area.

The findings of this study are that the ADCP worked but did not return meaningful data. This meant that the data from the ADCP deployments could not be used to achieve the aim of this project which was to develop a rainfall-recharge relationship for Sculpture Cave.

5.3 OTHER TECHNIQUES TO MODEL RECHARGE

The ADCP data was not giving a good indication of the amount of water flowing into the many swallow holes in the area around Sculpture Cave. An analysis of the variability in recharge was conducted using a previous study of recharge in the area. This looked at not only diffuse recharge but runoff as well. This is as in dry to average years most of the runoff is assumed to be captured by swallow holes. This hypothesis is still yet to be tested but is reasonable given the topography and proven swallowing capacities of the swallow holes in the region.
A model of the estimated potential recharge in the Katherine area was created by Jolly et al. (2000) from the daily rainfall record, using estimates for the end of dry season soil moisture deficit and daily losses (evapotranspiration etc). Subsequent modelling work in the Daly Basin (Knapton 2006) identified that of the potential recharge rate approximately 60 percent will be surface runoff and 40 percent recharge. Based on 60% of the potential recharge rate flowing from the 42 square kilometer catchment above Sculpture Cave into the swallow holes in the Sculpture Cave area, it was calculated that they may be contributing of the order of 15% of the spring inflow into the Katherine River over the period 1884 to 1999. The modeled estimates of the water year recharge resulting from the Sculpture Cave catchment is shown in Figure 57.

It is possible that recharge may be overestimated if a significant percentage of surface runoff flows past the swallow holes. Available data, however, does not allow a determination of the percentage of runoff that may bypass (see Figure 52) the swallow holes in the vicinity of Sculpture Cave.

Through the application of the model created by Jolly et al. (2000) the recharge to the Sculpture Cave area was able to be modeled (see Figure 57 for results), thus achieving the aim of the project. This model can also be applied to other swallow holes in the region but it may overestimate the recharge in wetter than average years as it assumes that all of the recharge is captured by swallow holes. This is of importance because the Katherine region is currently experiencing a period of significantly high rainfall (see Figure 35). It was hoped that the development of a rainfall-recharge model from the flow data into Sculpture Cave would provide an independent verification of the model developed by Jolly et al. (2000).

### 5.4 ASSESSMENT OF RAINFALL ANALYSIS

The Monte Carlo simulation can provide statistically valid rainfall data for Katherine that can be used to inform the assessment of the risks associated with using our current limited hydrological data sets. The simulation indicated that groundwater and surface water models that are developed utilising the existing 119 year rainfall record for Katherine should provide a sound basis for water allocation. The simulation also identified that current river flow and groundwater data sets are heavily biased to very wet periods. Water allocation based on these existing river flow and groundwater data sets will lead to over allocation of water resources.

The analysis also indicated that the mean water year rainfall of 1240mm that has fallen over the ten year period 1996/97 to 2005/06 may exceed the 99.7 percentile value for the rainfall likely to be experienced in any ten year period. This means that for the simulated 8000 years of rainfall data it would be expected that there would only be about 20 ten year periods during the last 8000 years when rainfall exceeded the rainfall experienced between 1996/97 and 2005/2006.

The rainfall variability in the region arises from variability in the climate system. The climate stems from a complex system that varies on many different time and space scales. This is evident from the analysis of the long term Katherine rainfall record with the variations at various temporal time scales evident in Figure 33, Figure 34 and Figure 35. The longer term variability is particularly evident in the Katherine rainfall record with a drier period that lasted 65 water years from 1899 to 1965 which was preceded and followed by extended periods of wetter years.
5.5 IMPACT ON WATER ALLOCATION PLANNING

The water control district (see Figure 13) as defined in the water allocation plan has been designated at “full development” (NRETAS 2009). Compared to regions in southern Australia the agricultural extent seems minimal but the irrigation occurring in the area is heavily dependent on groundwater (NRETAS 2009). There is a misconception that northern Australia has abundant water resources due to the sheer volume of rainfall it receives as a result of monsoonal activity. However this rainfall is concentrated in the period from December through to March, with the remainder of the year receiving very little rainfall. During this part of the year much of the north becomes a water scarce environment. This places a greater importance on systems such as the Tindall Limestone which due to their high storage and effective porosity are vulnerable to overexploitation.

In dry years there is virtually zero recharge to the Tindall aquifer, this is evident from the groundwater levels in NRETAS monitoring bore RN029429 in the mid 1990’s (see Figure 33). In terms of water allocation planning in these dry to average years discharge from the aquifer in the Tindal Limestone is critical in maintaining the flows required for the aquatic health of the Katherine River (NRETAS 2009). It has been noted in previous studies that the study of recharge via swallow holes such as Sculpture Cave is of importance (Knapton 2006).

Erskine et al (2003) recommended that flow regimes and environmental water requirements of Katherine River must be understood to set appropriate environmental flows and water licence conditions for large scale agricultural development and associated vegetation clearing. They recommended that no more than 20% of the stream flow greater can be extracted, and in very dry years no more than 8%. Potential recharge via swallow holes in the Sculpture Cave area has been calculated to be contributing of the order of 15% of the spring inflow into the Katherine River over the period 1884 to 1999. This indicates the importance of doing further work to quantify recharge in this area.

5.6 LESSONS LEARNT

One of the main outcomes of this project is stressing the importance of thorough groundwork before deploying equipment in the field. If this field inspection is not undertaken properly then the data may have little or no value. This is a serious matter when the site has been continuously maintained over many years. In addition in the case of Sculpture Cave this preliminary work should be undertaken by someone with a solid grasp of both surface and subsurface flows in the context of karst areas. The trial deployment in the wet season of 1996/97 of the ADCP at Sculpture Cave yielded flow measurements. The meaningfulness of these measurements was not investigated thoroughly before a commitment was made 3 years later in 2000 to permanently equip the gauging station.

The wet-dry Tropical environment of the study area presents unique challenges. The vegetation cover at certain times of the year can be formidable, whilst the same areas can appear barren at other times of the year. It is important to note that the rapid growth of native grasses and weeds in the wet season can make field inspections conducted in this time redundant.
CONCLUSIONS

Swallow holes are an important form of recharge in the Katherine area. The ADCP at the Sculpture Cave gauging station did not give a good indication of the point recharge occurring at either the cave or to the area. It was found that this was caused by insufficient groundwork being done prior to the ADCP deployments. This meant a rainfall-recharge relationship was unable to be constructed from the ADCP flow data.

The aim of the project was able to be achieved by applying the rainfall-recharge relationship developed by Jolly et al (2000). This produced modeled estimates of water year recharge to the swallow holes in the Sculpture Cave area for the corresponding historical rainfalls (see Figure 57). Further analysis of this modeled data found that recharge via swallow holes in the vicinity of Sculpture Cave may be contributing of the order of 15% of the spring inflow into the Katherine River over the period 1884 to 1999.

The Monte Carlo analysis of the rainfall indicated that currently the Katherine area is experiencing a period of unusually high rainfall. This means in terms of the water allocation planning that the data for Sculpture Cave was only acquired in a period of extreme rainfall.

The time-lapse camera proved a good tool for showing inflow into the cave. Although it proved even more useful in capturing wildlife activity as the water in the perched water table at Sculpture Cave is one of the few permanent water sources in the area during the dry season.
RECOMMENDATIONS

One of the main drivers for this project has been interest in reopening the gauging station at Sculpture Cave. The gauging station was closed down in 2006 due to faulty equipment. Recent times have seen a significant increase in funding for monitoring equipment. This has led to an interest in reopening the gauging station as it is a novel approach to a unique problem. However the results of this study show that the data collected had only qualitative benefit and as such in a quantitative capacity of measuring recharge it is of limited interest. The findings of the study are that in its previous form G8140025 should not be reopened.

It is recommended that a thorough site inspection should occur before the establishment of any gauging station in particular in karstic terrain. This site inspection should be undertaken by personnel who are well aware of the extreme heterogeneity expressed by karst terrains and the implications this has for both surface and subsurface flow.

The analysis of recharge through the swallow holes in the Sculpture Cave area undertaken in this study assumed that all of the runoff from the catchment recharges the Tindall Limestone aquifer through the swallow holes. It is possible that a significant percentage of surface runoff may flow past the swallow holes. Available data does not allow a determination of the percentage of the runoff that will bypass the swallow holes. A more comprehensive method of measuring recharge to the group of swallow holes near Sculpture Cave has been recommended. It is proposed that this be done by installing one gauging station upstream and one downstream of the Sculpture Cave area to capture the flow entering the swallow holes and the flow exiting this zone (see Figure 52) when the swallowing capacity is exceeded. This study identified the importance of thorough groundwork before deploying equipment in the field. If this field inspection is not undertaken properly then the data acquired may prove to be meaningless. A thorough examination of the catchment needs to be undertaken prior to the installation of these gauging stations. The data acquired from these gauging stations will then enable the recharge that is occurring through swallow holes in the area around Sculpture Cave to be more accurately quantified.

The method developed by Jolly et al (2000) and Knapton (2006) that enabled recharge in the Sculpture Cave area to be estimated should be applied to other swallow holes, or groups of swallow holes, in the unconfined Tindall Limestone aquifer in the Katherine region to model recharge. It will then enable the significance of this recharge mechanism to be better quantified and also identify other swallow holes where further detailed work is warranted.
REFERENCES


ACKNOWLEDGEMENTS

There are a few people whose contributions cannot go unmentioned. Danuta Karp and Anthony Knapton from Water Resources without whose work this would not have been possible. Phillip Richards for his oversight of the surveying work. Keith Smettem from SESE for giving me the freedom to explore this in my own way. And to the many others who helped me at various stages of this project, thank you.

Most of all I would like to thank my dad, Peter Jolly for all his help and support. It didn’t matter whether he was 3000km away on the phone guiding me through the tough times or in the middle of nowhere stuck holding a leveling staff he was always there for me.
## APPENDICE A  RAINFALL DATA FOR KATHERINE

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Notes:

* Data missing from primary data source. Data shown obtained from DR014923

## Data missing from primary data source. Data shown obtained from DR014904

# Data missing from primary data source. Data shown obtained from DR014903
NT Water Resources

Period: 4 Year  Plot Start: 00:00_01/01/1974
Interval: 2 Day  Plot End: 00:00_01/01/1978

DR014902  Katherine P.O.  10.00 Cumulative Rainfall (mm)
DR014903  Katherine Aero  10.00 Cumulative Rainfall (mm)
NT Water Resources

Period: 7 Year  Plot Start: 00:00_01/09/1957
Interval: 5 Day  Plot End: 00:00_01/09/1964

- DR014902  Katherine P.O.  10.00 Cumulative Rainfall (mm)
- DR014904  Katherine Exp. Farm  10.00 Cumulative Rainfall (mm)
| APPENDIX C | EVALUATION OF ADCM AT SCULPTURE CAVE AND COMPARISON TO EXPECTED INFLOW |
Evaluation of ADCM at Sculpture Cave and Comparison to Expected Inflow

February 2009
Evaluation of ADCM at Sculpture Cave and Comparison to Expected Inflow

Background
The gauging station G8140025 (53L 223578 8389165 MGA94) was installed at the entrance to Sculpture Cave (Figures 1 and 2). This cave feature was developed in the Tindall Limestone and is one of the main karstic features present in this formation. Sculpture Cave lies at a depression in the landscape and receives the runoff from further up in the catchment. Due to its ability to channel runoff directly to the water table through caves and conduits in the subsurface it is designated as a swallow hole. An Acoustic Doppler Current Meter (ADCM) had been installed at the site in order to quantify the inflow into Sculpture Cave.

Figure 1: Site Location

G8140025 History
The ADCM was deployed at the site (Figures 1 and 2) for the duration of the wet season with it being removed from the site for the duration of the dry season. It was first installed in February 1997 with the next redeployment being in the 2001/02 wet season at which point it was reinstalled every wet season up till 2005/06. From these deployments data was obtained for the 96/97(partial), 01/02 and 02/03 wet seasons. In the 03/04, 04/05 and 05/06 wet seasons the ADCM was affected by recording issues and battery problems.
ADCM Placement

The exact installation location of the ADCM is shown in Figure 2 with a side profile of the site being depicted in Figure 3. This location was chosen because it posed minimal logistical issues as opposed to an in-situ cave installation. It also maximised the chance of recovering the equipment at the end of the wet season. As a result, there would have been some tradeoffs in the measured data. Firstly, the ADCM was installed on a mound of limestone rubble from a previous collapse of the cave roof (Figure 3). This mound is of a cavernous structure with voids at least 2 to 3 m deep where water can easily pass through (see Figures 4 and 5). This could prove important if this is the main flowpath for inflow into the cave. The installation of the ADCM in front of a large boulder (Figures 2 and 3) could have interfered with the flow recorded at the ADCM. The cross-sectional area calculated at the ADCM site would also introduce errors into the inflow measurements due to the non-uniform cross section and distance from the cave entrance (Figure 2).
Comparison of ADCM to Other Techniques

The quantification of inflow into a swallow hole in this region presents several logistical challenges. Most other techniques such as dye concentrations or manual flow measurements are inadvisable due to the magnitude of the wet season flows.
ADCM Data

The ADCM recorded 19 flow events during the 3 wet seasons it was able to record data, these events are shown in Table 1.

Table 1: Recorded Flow events

<table>
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<tr>
<th>Event</th>
<th>Start</th>
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<th>Inflow (ML)</th>
<th>Duration (hours)</th>
<th>Max Flow (cumecs)</th>
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A selection of G8140025 flows were plotted in Figures 6 to 9. These plots also contain groundwater level logger data from RN008221 and RN029429 (when available), and rainfall data from R8140002 and R8140003. Site locations of these stations are shown in Figure 1.
Figure 6: 2002/03 Wet Season Flow Events

Figure 7: Flow from February of 2002
Figure 8: Flow from January 2003

Figure 9: Flow from January to February 2001
Discussion of ADCM trends

An earlier speleological assessment of the area suggests that the regional flow direction is in the direction from Cutta Cutta Caves towards Sculpture Cave (Report 63/1993, Lauritzen and Karp 1993). The flow events recorded by the ADCM indicate that Sculpture Cave is hydraulically linked to the karst conduits below with there being a strong correlation between recorded flow events and rise in water table at RN008221 Cutta Cutta Caves (Figures 6 to 9). However Sculpture Cave is probably not responsible for the rise in RN008221 with this influx of water being a result of possible inflow from the sinkholes marked in red in Figure 11. However it does provide an indication of the behaviour of the water levels in the main karstic conduits in relation to the regional rainfall.

It is important to note that ADCM measurements are always accompanied by a rise in RN008221 levels and sizable rainfalls in the catchment, see Figure 7. However there are quite a few events where there has been a sizable rise in RN008221 and significant rainfall at both R8140002 and R8140003 but no flow recorded at G8140025 (see Figures 8 and 9). Table 2 shows the relationship between groundwater levels and flow events, it must be noted that it is possible these water levels reflect different karstic conduits but overall they provide an indication that flow at Sculpture Cave does not depend on the height of the water table but rather the magnitude of the runoff off the catchment. Figure 9 is especially interesting because in late January it had a significant quantity of intense rainfall yet no record of flow at Sculpture Cave. This seems unlikely and it seems that there is a threshold flow that the runoff must reach before it is able to rise above the level of the ADCM.

It has already been suggested that flow bypasses the ADCM location through cavernous voids in the mound it is installed on (see Figures 3, 4 and 5). These small caves could hold sizable flows and upon exploration of the cave there is a small cave on the inner left hand side which extends beyond the cave entrance with a number of surface openings of the cave visible on the approach to the cave. These make measuring the total flow into the cave logistically very difficult and/or impossible.

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Runoff Determination

The gauging station at McAdden Creek (G8140158) is 15km NNE of Katherine and receives minimal groundwater input. This makes the flow data obtained from this station for all practical purposes analogous to the runoff from the catchment. Katherine regional rainfall cumulative distribution for 2001/02 is shown in Figure 10 and shows that the rainfall characteristics over the Katherine region are similar and as such the Sculpture Cave recharge area should be able to be characterised by the McAdden runoff. The runoff data from this catchment (in millimetres) can then be used to determine the expected runoff from the Sculpture Cave catchment.

Figure 10: Comparison of Katherine regional rainfall distributions
Catchment Boundary and Runoff Determination

The catchment boundary (Figure 11) for Sculpture Cave was delineated from elevation data and topographic features. This catchment boundary should be representative of the recharge area to Sculpture Cave. This provides a catchment size of 42km² for Sculpture Cave. Using this catchment size and the runoff in millimetres for the G8140158 catchment the expected runoff for the Sculpture Cave catchment can be computed. Figure 12 shows the comparison between expected runoff and cave inflow. The flow at G8140025 only accounts for approximately 10% of the expected runoff.

Figure 12: Comparison of Expected Runoff and Measured Cave Inflow
Results

The ADCM recorded flow does not account for a significant proportion of the expected flow. This is to be expected because karstic terrains are extremely heterogenous and even on the approach to the cave there were openings to underground conduits clearly visible. In quantifying the volume entering the system through Sculpture Cave the ADCM deployment has been unsuccessful. It has however captured a variety of very peak events and from these it can be estimated that the maximum "swallowing" capacity of the karstic conduits Sculpture Cave is directly linked to is in the order of 7.5 cumecs.

In determining the catchment for Sculpture Cave two other sinkholes of interest were identified in the general vicinity. These two sinkholes are situated between Cutta Cutta Caves and Napier Road adjacent to the fence line (marked by two red dots in Figure 11). These sinkholes have a catchment similar in size to Sculpture Cave however they receive the runoff from the adjacent farms along Napier Road.

Further work at Sculpture Cave

In January 2009 two water level loggers were placed into a PVC pipe in a cavernous void (2.2m deep) adjacent to the ADCM install location (Figure 15). The (drilled) PVC pipe was secured by a cross bracket at the surface (Figure 13) and appeared relatively fixed in place at the bottom by the cavern. Two loggers were used to provide a failsafe if one logger fails (Figure 14). The data obtained from these loggers will hopefully clarify the significance of the flows through the voids. However karst terrains can be unpredictable and it is possible that water may not pond that frequently in the voids if they themselves are connected to other voids and/or conduits. The loggers will be retrieved at the end of the 2008/09 wet season.

Recommendations

Future gaugings at Sculpture Cave should be reconsidered. This is because the nature of the site makes it impossible to measure a significant proportion of the expected flow into the cave, unless a control structure such as a flume is installed to regulate the inflow some distance from the cave. This structure would have to be significantly large and its construction within a national park would prove difficult. Future studies should investigate if it is possible to measure the flows running off the farms on Napier Road towards the two sinkholes marked in red in Figure 11. This could be initiated by first determining the nature and flowpaths of the water running off the farms by talking with local people who live and work in the immediate area. If flow measurements at these sites are feasible then they would provide easier access than Sculpture Cave and depending on the suitability of the sites they could possibly quantify total inflow off their catchment, a relationship that then could be applied to Sculpture Cave.
Figure 13: Logger installation adjacent to ADCM mounting

Figure 14: Two loggers were placed at a depth of 2.1m and 2.2m

Figure 15: Final logger installation