An Ecohydrological Model of Waterbird Nesting Events to Altered Floodplain Hydrology

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EXTENDED ABSTRACT

River regulation and water extraction alters the natural inundation patterns and ecological responses within floodplain wetlands. Ecohydrology is an emerging discipline that is important for determining how the modification of hydrological cycles affects such water dependant ecosystems. We present an ecohydrology model (IQQM-ZIP) that assesses the effect of flow regime on the size of waterbird nesting events in an intermittently inundated and hydrologically modified wetland, Booligal Swamp (Lachlan River, Eastern Australia).

This paper introduces a mixed regression model, Zero Inflated Poisson (ZIP), which is the Poisson regression conditional to an occurrence model. ZIP is suitable for count data (such as number of nests) with many zeros (in this case, many dry years without nesting events). In this study, a hydrological model assembles eight candidate predictors that are discrete annual time series. The rationale and the statistics of the final calibrated ZIP model are discussed. The three chosen predictors assert that sustained inundation, severity of the preceding drought and the nesting availability at alternative (~1000 km north) sites contribute to the water bird colony size. The model simulates the nest numbers with a pseudo R^2 of 0.92 (df =13).

The long term hydrology (1898 to 2005) under current flow regulation and predevelopment condition is simulated using the hydrologic model, Integrated Quantity Quality Model (IQQM). The IQQM-ZIP simulation demonstrates a decrease in annual ibis nest count (p=0.08%, df=104) due to development, see Figure 1. The decrease is limited to medium to low density (less than 40 thousand) nesting events. This simple model informs the development of an appropriate long-term flow regulation plan (including consideration of any climate change) that increases the chance of ibis juveniles achieving independence.

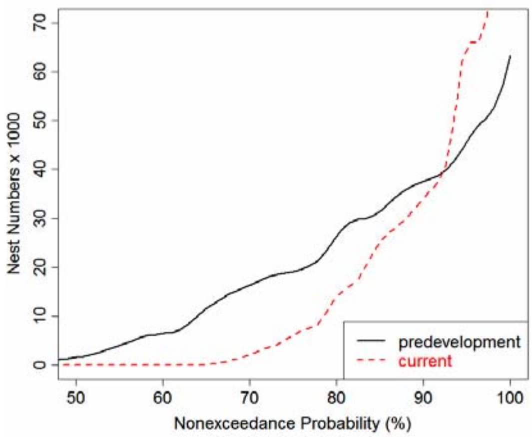

Figure 1. The non-exceedance graph of average annual ibis nest in predevelopment and current hydrological case.

1. INTRODUCTION

Booligal Swamp of the lower Lachlan River is a nationally significant wetland known for its capacity to support large waterbird recruitment events within high-density lignum (*Muehlenbeckia florulenta*) dominated habitat. Lachlan River is an arid stream of 1000 kms of main channel draining a catchment area of 85000 km^2 in Eastern Australia. The river has several regulating storages, weirs, wetlands, and major irrigation developments. The climate record in last century exhibited long-term persistence such as 5 to 10 years of drought sequence followed by a similar length of wet sequence. Lachlan River has many wetlands of high conservation significance (EA 2001). This paper introduces a composite modelling platform (hydrology plus ecology) to monitor the effect of the flow regulation in terms of water bird habitat.

This paper is organised as follows. We first provide a background of our research followed by hydrological and ecological aspects relevant to the case study. The theory and application of the ecological model is explained in Section 5 and 6. The long term effect of flow regulation on ibis breeding, simulated using the calibrated ecohydrology model here, is presented towards the end of this paper.

2. BACKGROUND

Wetlands act as an environmental refuge, in the context of generally dry and highly variable climate of Eastern Australian catchments. They support various aquatic and terrestrial ecosystems. Wetland types vary widely and the scope of this paper is limited to the intermittently inundated inland floodplain wetlands in arid region. Human activities such as river regulation and drainage have significantly altered the natural inundation pattern of these wetlands. A case study of 12 floodplain wetlands on the Lachlan River showed a distinct drop of inundation period of all the wetlands due to development. Environmental flows rules are legislated by the NSW Government in recent years to improve the overall water health including wetlands. A variety of studies since 1997 have examined the responses of wetlands (among others) to environmental flows (Chessman 2003). In Lower Lachlan Wetlands the increased inundation due to environmental flow rules is estimated to be 10% (Driver *et al.* 2005). Ecohydrological models quantify the benefit or otherwise in ecological terms such as habitat improvement of the waterbirds. The following paragraph is included to flag this emerging discipline of ecohydrology to the readers.

The new paradigm of ecohydrology has been acknowledged in recent times (Baird *et al.* 2004; Dunbar and Acreman 2001, Rodriguez-Iturbe 2003). This integration of Darwinian expression and Hortonian principle is increasing in popularity because it helps natural resource managers respond to a future of continual environmental change. Ecohydrology investigates how hydrological process influences ecosystem or conversely how feedback from the biological communities affect the water cycle. Hannah *et al.* (2004) identified a doubling in number of research papers that referred to this multidisciplinary term from 1999 to 2003. The American Geophysical Union 2005 Fall Meeting, with over six thousand attendance, included a tutorial on this topic (Newman and Breshears, 2005). In Australia, the Murray Flow Assessment Tool (MFAT) by Young *et al.* (2003) is an example of an ecohydrological model in practise. We present here an ecohydrology model (IQQM-ZIP) that assesses the effect of flow regime on the size of waterbird nesting events.

3. HYDROLOGY

Hydrology plays a fundamental role in the ecology of various wetland dependant organisms. The lack of human settlements around any remote wetland means that important hydrological information such as long time series of water depths, wetting and drying regime, flow velocity and volumes are often not recorded. Rain gauges in Australia, similar to many other countries, are spatially and temporally more frequent than other types of hydrological measures. There are various hydrological models that can transform rainfall into variables such as inundation frequency, wetting and drying cycles, temporal pattern of favourable breeding condition of water birds, in absence of any long-term wetland data.

The hydrologic model used here is the Integrated Quantity Quality Model (IQQM) that was progressively developed in the 1990s by the NSW Government in Australia (DLWC 1999; Simons *et al.*, 1996). This is a deterministic model that mainly simulates rainfall runoff, river routing, flow regulation and extractions. The inflows from the various tributaries to the Lachlan River are calibrated based on concurrent records of sub-catchment rain and tributary flow records of mainly fifties to late eighties of the twentieth century. The overall river flow routings, loss and irrigation extractions are calibrated for a period of 1981 to 1997. The calibration details were published earlier (Hameed and Podger, 2001) and the calibrated model has been applied in various water management studies (Chowdhury and Hameed, 2005) including the development of the

Lachlan Water Sharing Plan (NSW Government 2003). Readers may refer those publications for technical details of IQQM.

The Lachlan River flow at various locations is compared against the drying and wetting of the Booligal Swamp. Local knowledge, field observations (like increased water bird activities) and river hydraulics all indicate the inundation of Booligal Swamp commences at a flow of about 2500 ML/d at the river gauge at Booligal Weir (Driver *et. al* 2005). Thus Lachlan IQQM simulates the inundation of Booligal Swamp based on the flow at the weir.

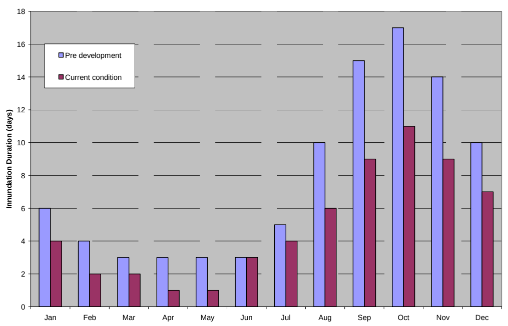

Figure 2. Decrease in long term average monthly inundation period of Booligal Swamp due to development

The Lachlan IQQM simulation is based on climatic data of 1898 to 2005. The long simulation provides an opportunity to analyse long-term ecological responses modelled based on these hydrological predictors. The ‘predevelopment’ hydrology of the river is simulated by removing all developments including the reservoirs, weirs and irrigation extractions from the calibrated Lachlan IQQM. The model demonstrates a drop in average inundation (Figure 2) of Booligal Swamp due to development. The effect of this decrease on water bird breeding is investigated here.

4. ECOLOGY

Ibis recruitment responses to wetland inundation are relevant to management because these species numerically dominate colonially nesting events within southeast Australia. The combined abundance of three species of ibis provides a relatively easily measured indicator of the success of overall colonially nesting events across the Murray Darling Basin (MDB). The abundance of large waders, which tend to be numerically dominated by Sacred Ibis (*T. molucca*) and Straw Necked Ibis (*Threskiornis spinicollis*), declined by 91% during 1983-2001 (Kingsford and Thomas 2004).

Figure 3. Glossy Ibis (courtesy: www.commons.wikimedia.org).

Booligal Swamp supports some of the largest recorded breeding populations of Glossy Ibis in Australia (Magrath 1992). The flow management in Booligal Swamp historically has focused on three relatively abundant bird species, Straw-Necked Ibis, Sacred Ibis and Glossy Ibis (*Plegadis falcinellus*), Figure 3. The breeding activities of ibis are recorded using a count of bird nests during the spring to summer period of 1969 and 1984 to 2000 (Driver *et al.* 2005).

5. ZERO INFLATED POISSON MODEL

There are various regression and non-parametric options for predicting longitudinal data, of which a widely used approach is generalised linear regression. Generalised linear model predicts the mean of the distribution of the response variable (McCullagh and Nelder, 1989), the response is mapped to the exponential family of distributions, here the Poisson distribution. Poisson distribution provides a standard framework to analyse data that are non-negative integers, such as count data. However, ecological data often includes higher incidents of zero counts than would be expected to occur randomly in a Poisson distribution. Figure 4 demonstrates a synthetic case of such variables. These zeros have special significance (Martin *et al.*, 2005), as occurs in this case study on the effect of periodic drought on water bird breeding. A mixture distribution called Zero Inflated Poisson (ZIP) is used to model the Poisson data with excess dispersion at zero (Ridout *et al.* 1988, Bohning *et al.* 1999). The density function is as follows:

$$f(y \mid p, \lambda) = \begin{cases} p + (1-p)e^{-\lambda}; y = 0 \\ (1-p)e^{-\lambda}\lambda^{y} / y!; y > 0 \end{cases} \quad (1)$$

Equation (1) shows that the distribution *ZIP*(p, λ) has two parameters, viz the mean count λ and the probability of the occurrence p. The following linear regression pairs specify the model.

$$log(\lambda) = X\,\beta \qquad (2)$$

$$log\,[p/(1-p)] = Z\,\gamma \qquad (3)$$

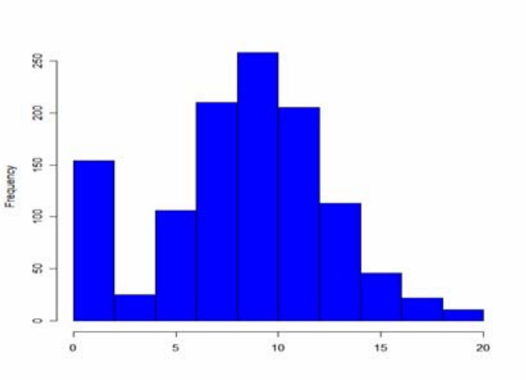

Figure 4. Synthetic example of Zero Inflated Poisson data where mean is 10 excluding the extra zeros.

X and Z are the predictor vectors. The parameters of this model are β and γ estimated by maximising the *likelihood* of the predictions. The *likelihood* is the joint probability of the predictions given the distribution of the true response, here *ZIP*(.,.). The expected value of the response of this model is (1-p)λ. Note that ZIP was further extended into multivariate cases at later research (Li *et al*., 1999, Walhin 2001).The multivariate ZIP model may be used to simulate a family of longitudinal records of multiple biological counts living on the same intermittently inundated wetland.

6. ZIP MODEL FORMULATION

6.1. Predictor Selection

The choice of initial pool of candidate predictor is vital to attain desirable accuracy of any cause and effect regression model. The choice is often limited by the availability of records of the required measures. Our initial pool of predictors has eight candidates as listed in Table 1.

The candidate predictors include rainfall and flows at the vicinity of the Booligal swamp representing the breeding conditions such as the extent of inundation and food availability. We have also included inflows to the Borders Rivers in the north to simulate the effect of availability of alternative habitat. The Borders River flow signifies rain and flow data of southern Queensland, which is situated 1000 km North of Booligal Swamp, One of the motivations of using these rainfall and flow records (or estimates) is that they contain long records (for a period over a hundred years).

Table 1. Candidate Predictors.

Candidate Predictors	Symbol
1. Annual Rainfall at Booligal (mm)	*rainY*
2. Aug – Dec: Rainfall at Booligal (mm)	*rainS*
3. Aug – Dec: High flow days at Booligal	*durS*
4. As item 4 in quadratic (day^2)	*durS*^{2}
5. Months since last inundation at Booligal	*gap*
6. Aug – Dec: Flow volume at Booligal	*volS*
7. Annual inflow to the Border Rivers	*QldF*
8. Annual rainfall at Toowoomba (mm)	*QldR*

Candidate predictor variables may exhibit significant inter-dependences. The retention of correlated predictors leads to over fitting and poor prediction skill, which is known as multi-colinearity. The *deviance* of a Generalised Linear Model (here Poisson Regression of non zero nest counts) is a measure of residual variation about the fitted model. Lower *deviance* implies a better fit. Now the best subset is selected as follows. Each candidate predictor is removed from the full model (ie. model that includes all eight predictors) and the increase in deviance is computed. The smaller the increase the less important the predictor is. The predictor with smallest increase is removed first and the process is repeated again (Kleinbaum *et al*., 1998). Table 2 lists the first trial of removing the predictors from the full model of Equation (2). Note that this study used bird nest counts in units of thousands when computing *deviance* reflecting the accuracy of the measures. The third column indicates the probability that the measured increase in deviance may occur by random chance. The last column of this table shows the predictors that are retained in the final model. Note that an alternative search based on least square assumption (not shown here) yielded the same predictors.

Table 2. The increase of *deviance* from the full model due to removal of predictors. The higher the deviance the stronger the predictor is.

Predictor	Deviance	$Pr(>\|\chi^2\|)$	Retained
rainY	60.8	0.70	No
rainS	62.6	0.16	No
durS	79.4	2e-5	Yes
durS^2	104.	4e-11	Yes
gap	119.	2e-14	Yes
volS	62.1	0.23	No
QldF	68.9	4e-3	Yes
QldR	60.8	0.69	No

The occurrence of nesting event, Equation (3), is predicted using logistic regression that assumes a binomial distribution of the response variable. Similarly to the Poisson model, the full model *deviance* is compared with backward removal of each predictor, the details of which is omitted due to space. The logistic regression model retained *durS* as the only predictor.

6.2. Selected Model

The selected model to predict nest count (λ) and nesting occurrence (p) retained the following predictors X={*durS*, *gap*, $durS^2$, *QldF*} and Z={*durS*} respectively, see Table 1 for the notation and units. The selected model statistic is shown in Table 3. We explore the ecological rationale of the predictors of the selected model. The inundation duration (*durS*) during breeding season was identified as a key determinant of breeding environment in past studies (Magrath, 1992, DWR 1993), which has been validated by the regression model here. Another interesting feature is the significance of the severity of the preceding drought (*gap*). It has been confirmed in the several studies that inland wetlands are most productive when flooding follows a period of complete drying (Maher and Carpenter, 1984). Magrath (1992) anticipated that the longer dry phase would trigger greater production of detritivores, implying food abundance for the waterbirds.

Table 3. Parameters estimates listed in order of decreasing importance.

Predictors(X)	**β**
Intercept	6.900
durS	0.078
gap	0.020
$durS^2$	-0.0004
QldF	-0.0011
Predictor (Z)	**γ**
Intercept	6.24
durS	-0.327

We draw attention to the likely rational of the negative sign of the $durS^2$ and *QldF*. The negative quadratic duration implies that the significance of inundation diminishes in case of very prolonged flooding of the wetland, a phenomenon not unexpected. The negative *QldF* suggests that if water is available in wetlands that are closer to Queensland coastal winter refuges (e.g., the Gwydir Wetlands and Narran Lakes) then the ibis are less likely to move south; consistent with recent studies (Dingle 2004).

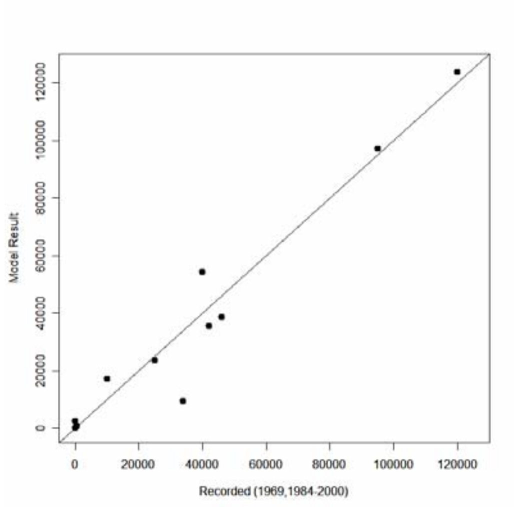

Figure 5. The calibrated ibis nest count is drawn against the recorded counts.

6.3. ZIP Calibration Result

The model was calibrated for the data period of {1969; 1984, 1985…2000}. The calibration result is drawn in Figure 5. The pseudo R^2 is defined as the ratio of the residual *deviance* over the NULL *deviance*, which is 0.92. The results are significant at $Pr(\chi^2) < 0.001\%$ with 13 degrees of freedom. Despite the promising test statistic, due to the small degrees of freedom, limited predictor choice (eg. hydrologic only) and small number of non-zero events, we recommend this model for simulation studies only as presented in this paper.

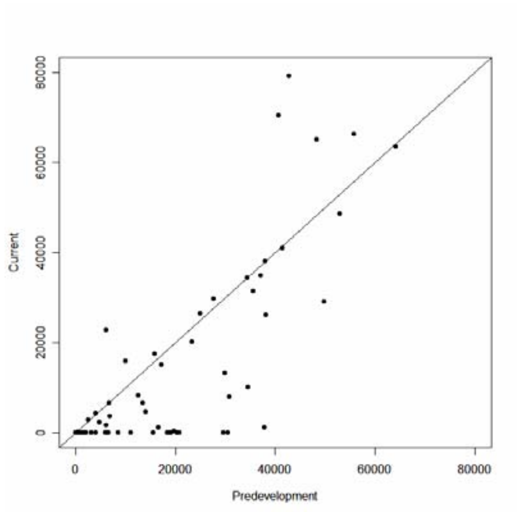

Figure 6. The simulated ibis nest numbers of current flow regime is drawn against pre development condition.

7. RESULTS AND DISCUSSION

The climate variability is represented by a hydrological time series of 1898 to 2005. Lachlan IQQM is used to simulate the variable *durS* and *gap*. Similarly the Border Rivers IQQM is used to simulate the variable *QldF*. The simulation result, in Figure 6, shows an overall drop in the nest number due to development. The decrease of nest count is found statistically significant when analysed by one tailed paired t test (p= 0.08% and df=104). The non exceedance plot of bird nest count in Figure 1 illustrates that the developments reduced the the medium to low density breeding events (less than 40000 nest count). This phenomenon reflects the observation that the river regulation alters medium to low level natural inundation duration. Note that the current river water management regime maintains the occurrence and duration of floods in Booligal Swamp partly by using translucent environmental flow rules (Hillman *et al*. 2003) which are designed largely to mimic the natural flood cycles. The effect would be more pronounced in absence of these environmental rules. Future studies shall analyse these changes in nesting pattern in greater details. This model can be applied to assess the effectiveness of various environmental flow rules in terms of water bird breeding. This simulation is based on stationary climate variability (historical 1898-2005), however the IQQM-ZIP can quantify the effect of various future climate change scenarios on water bird nesting.

8. CONCLUSION

The ecohydrology model IQQM-ZIP uses IQQM hydrological model, which in turn feeds into a mixed regression model ZIP. The three chosen predictors of ZIP assert that sustained inundation, severity of the preceding drought and the nesting availability at alternative sites contribute to the water bird colony size. The ZIP model predicts the observed nest numbers with a pseudo R^2 of 0.92 (df =13).The IQQM-ZIP model confirms that for the representative climatology from 1898 to 2005, the development and river regulation has reduced (p=0.08%, df=104) the average annual ibis nesting frequency. However the reduction in nest count only occurred during the breeding events of less than 40000 nests.

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