

A Post Keynesian Ecological-Economic Model of Agriculture in a Regulated River Basin

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Abstract

Extreme drought and land degradation currently afflict the Murray-Darling river basin, the source of inland water for the food bowl of Australia. At present there is no non-equilibrium *economic* modelling approach with appropriate policy levers to address these problems, although there does exist a realistic *ecological* model called River Manager. What is needed is an equally realistic economic model that embraces the complexity of interactions at the individual crop sector level within the basin, and can also be linked to the River Manager model of its ecosystem. This paper is a major step in the authors' research project of developing a non-equilibrium modelling approach to what eventually will become a fully-specified and policy-oriented model of the Murray-Darling Basin.

This paper employs post Keynesian economic theory and complex systems modelling to tackle the ecological challenges. The focus is on a generic regional agricultural economy that comprises a regulated river basin and includes crucial ecosystem services, especially water. The aim is to build a tool and set up a process for making diagnostic projections (not forecasts) of the impact of farmers' business strategies on the ecological and economic systems within the river basin, and the way in which various government policies can modify these impacts.

Computer simulation exercises show that it is possible to integrate a demand-based economic model with a supply-based two-crop river basin land-use model. Testing the model, in both constrained and unconstrained ecological variables, conveys an understanding of its nature and viability, from both the model-building and political economy perspectives. The ability to unite a supply-based ecological model with a demand-based economic model provides strong encouragement for further research into this modelling approach that has ecological constraints incorporated into a dynamic non-equilibrium macroeconomic model equipped with sub-models of two agricultural crops: irrigated rice and rainfed wheat.

The next iteration of the model will add more crops, including a 'crop of last resort' (rainfed fodder). Once a proof-of-concept economic model is successfully developed, our aim is to merge it with the River Manager model to create an integrated Economic and Ecological Sustainability Model for the Murray-Darling Basin (EESM:MDB).

Two observations are made from the perspective of pure economic theory. One is that the current general equilibrium modelling approaches to ecological-economic integration are inadequate, and for the same reasons that post Keynesians have long criticised the mainstream's macroeconomic theories, underpinned as they are by the Walrasian general equilibrium model. The other observation is that Lotka-Volterra biological models of predator-prey dynamics have similarities with the type of ecologically constrained profit-based economic cycles shown in this paper. Much needs to be done in this area, and urgently, if the devastation of the ecosystem is not arrested and reversed.

Introduction

In their single-minded pursuit of economic growth, economies the world over are facing serious environmental challenges with the scientific evidence clearly identifying climate change, depletion of oil resources, water scarcity, soil degradation, the collapse of fish stocks, and the chronic loss of biodiversity as central concerns (Jackson, 2009). More specifically, a recent economist's report states that Australia, in its success of achieving strong economic growth, is more highly exposed to the impacts of ecological concerns – and particularly climate change – than other developed economies due to four factors: (i) dry and variable rainfall-temperature continent, (ii) major agricultural base, (iii) terms of trade sensitive to Asian climate change impacts, and (iv) fragility of nearby highly exposed developing economies (Garnaut, 2008a). The first two factors point directly to the agricultural and pastoral economic core of regional Australia and its ability to adapt in meeting such challenges. The climate change challenge is particularly crucial in Australia because, along with USA and Canada, current CO₂ emissions are four times the global per capita average (Garnaut, 2008b, p. 31).

This paper employs economic theory and modelling to tackle one specific aspect of the ecological challenge. The focus is on a generic regional agricultural economy that comprises a regulated river basin and includes crucial ecosystem services, especially water. The aim of the modelling methodology is to set up a process for making diagnostic projections (not forecasts) of the impact of farmers' business strategies on the ecological and economic systems within the river basin, and the way in which various government policies can modify these impacts. Without such an integrated ecological-economic model, it is not possible to identify ecologically unsustainable farm business practices and solutions to challenges currently facing such a river basin economy and its environment. There is particular concern with the extreme drought and land degradation (salination, pollution from fertilisers, soil erosion) problems afflicting the Murray-Darling river basin, the source of inland water for the food bowl of Australia. The authors are tackling the problem that there is no non-equilibrium modelling approach with appropriate policy levers; one that embraces the complexity of interactions at the individual crop sector level within the basin, and can also be linked to ecological models of sustainability. This is a major step in the authors' research project of developing a non-equilibrium modelling approach to what eventually will become a fully-specified and policy-oriented model of the Murray-Darling river basin.

The next section outlines current approaches and their inadequacies in modelling the integrated ecosystem and economy of an agriculture-based river basin. An alternative post Keynesian complexity modelling approach is specified in the following section. Using this approach, a generic river basin model is outlined with projected outputs and policy implications. Concentration in this model is on agricultural production in the river basin and the ecosystem processes relating to climate change, water supply, land degradation, and carbon emission. The final version will have a 'front end' with a real-time interactive graphical interface for displaying the resulting spatio-temporal data, allowing users to adjust policy levers and immediately observe the short-, medium- and long-term consequences. The mathematical details of the river basin model are then specified, with implications for future theoretical developments into a more sophisticated integrated ecological-economic model. Finally, a short conclusion on the theoretical and policy implications will round off this paper.

Current Approaches

There are two conventional modelling approaches in the current discourse on integrating the ecosystem and the economy. One is rooted in ecological physical sciences modelling with attempts to incorporate existing standard economic models. The other approach has come from mainstream economists adopting ecological models of species interaction and modelling economic processes within. This section outlines an example of both approaches to highlight their serious limitations and the need for the heterodox approach developed in the next section.

From the crisis of the Murray-Darling Basin (MDB), the CSIRO¹ has had a 15 year research project beginning with hydrological work on the Integrated Quantity and Quality Model (IQQM) for the MDB's water catchments. This model is described in Simons et al. (1996) and Hameed and Podger (2001). IQQM carefully specifies MDB's topography, hydrology, microclimates, soil types, forestry, etc.. Based on Welsh and Podger (2008), the IQQM has morphed into a larger River Manager/River Operator model under the auspices of the CSIRO's eWater Cooperative Research Centre. This modelling project is connecting the various surface and groundwater models that describe the 18 sub-regions within the MDB region. Using computer simulation, the River Manager framework carries out up to 70 model runs to generate results for each scenario over a 111 year modelling period. This is a deterministic model which runs in a range of time steps from daily and weekly to monthly. Podger et al. (2008) describe the results from their project as providing the most accurate assessment, to date, of the available water resources in the MDB. They show how the impacts of climate change, farm dam development and groundwater extraction impact on local regions and throughout the MDB, as well as identifying the relevance of these impacts from both a local and basin-wide perspective. Based on published work on the IQQM, the River Manager Model specifies multiple crops and other land uses, plus actual hydrological and ecological specifications in a dynamic setting over a long time horizon.

In a complementary study, Young et al. (2008) note that the hydrological information inputs into the eWater CRC water modelling comprise only one of the important components of a broader assessment, which must include the social, economic and environmental consequences of expected changes in water availability. The River Manager team are well aware of this need, but limited resources have forced eWater CRC to place the modelling of economic impacts at the bottom of their "action list". As a result, they are intending, in the short-term, to incorporate a standard mainstream computable general equilibrium (CGE) model.² This means that the economic component will specify the economic behaviour of each agent in the region as operating under the neoclassical assumptions of "rational economic man", with all the limitations that that entails (Hollis and Nell, 1975). Also, there is a serious modelling problem with the integration of the ecosystem and the economy. The dynamic non-

¹ Commonwealth Scientific and Industrial Research Organisation. See Collis (2002) for the history of the CSIRO.

² In an email communication on 15 January 2010 to one of the authors, Dr. Peter Wallbrink (Executive Manager: River and Catchments, eWater CRC, CSIRO) stated: 'Specifically regarding the economic impacts and economic change aspects, these have fallen to the bottom of our action list...Realistically any functionally (sic) in these domains will be many years away.'

equilibrium ecological model of the River Manager/River Operator project is incompatible with the static neoclassical economics CGE modelling approach. The long time horizon with simulation of scenarios does not fit well with the simultaneous equation form of the general equilibrium economic model.

Rather than separately, as in the River Manager modelling project, the second approach stresses the need for ecological and economic systems to be jointly determined. This is because important ecological variables are dependent on economic variables, and also the other way around. Thus it has been strongly argued that the modelling approach should integrate ecology and economics to capture important intersystem feedbacks (Amir, 1979; Perrings, 1987; Wätzold et al., 2006).

Ecological economics has recognised the lack of integration by neoclassical resources economics with the type of ecological systems described above in the River Manager project (Costanza and Daly, 1987). In response, governments have funded interdisciplinary work between ecologists and evolutionary economists (Tschirhart, 2009, p. 386). One example is a study by Finnoff and Tschirhart (2008) on the Alaskan marine ecosystem and that state's economy, using a dynamic computable general equilibrium economic model with an adaptive general equilibrium ecosystem model. The integration is based on the Lotka-Volterra biological model of plants and animals on how predators expend time (dynamics) to capture and consume prey up to optimal satiation of foraging (Lotka, 1925; Volterra, 1926). In this integration ecological economists have used this predator-prey competitive model to derive self-limiting growth (Tschirhart, 2009).

The integration of ecological and economic concerns in a dynamic setting is to be applauded. However, there are two serious limitations that this approach cannot address. The first is the assumption of optimality in both the ecological foraging process and the economic trade-off of benefits and costs of predation. Courvisanos (2009), from the perspective of Post Keynesian analysis, identifies the optimality determinant of equilibrium to be unjustifiable in the real non-ergodic world where fundamental uncertainty requires all agents to operate within the context of satisficing conventions. The optimality of some ecological steady state, as proposed by Costanza and Daly (1987) is as much a chimera as the neoclassical nirvana of perfect competition.

The second limitation is related to the ecological world in which river basins like the MDB exist. In such regions, climate change and resource depletion come from human economic activity engaging with the ecological system, and not some pure biological predator preying on another. This goes to the heart of the implied general equilibrium assumptions of this model, in which there are numerous identical predators and prey optimising their energy profits and utilities respectively with no monetary system or valuation. Thus, there are no firms that can accumulate capital goods and market power. The only agency is individual predators and prey in a biologically ergodic world. Finally, there is no form of government or "regulator" of an area like the river basin that ensures public accountability of the quality of natural resources like water and air.

Alternative Post Keynesian Complexity Modelling Approach

Having identified the limitations of current approaches to modelling the integration of the ecosystem and the economy, this section sets out an alternative approach for modelling a regulated river basin model of agricultural production. This model integrates the ecological river basin system with an existing non-equilibrium post Keynesian macroeconomic model disseminated by the authors over a series of computer simulation experiments in previous published papers.

The modelling begins with an alternative economic approach developed from research done by post Keynesians to handle non-ergodic fundamental uncertainty as an epistemic instability of beliefs, reinforced and magnified by institutional features in financial markets and technological change (Runde, 1991, pp. 142-3). A behavioural motivation in this approach to decision-making underlies economic instability, resulting in a non-equilibrium open system based on historical-time processes with a monetary system and cumulative causation of investment in capital goods and accompanying path dependence in the system's evolution.

The investment decision-making dynamics in this approach originate with the work of Michał Kalecki on investment cycles and increasing risk, in which profits derived from effective demand provide both ability and incentive to invest (Kalecki 1939). Kaleckian foundations deliver an investment cycle of corporate instability due to entrepreneurial uncertainty built into conventions and rules that are sensitive to information about the unknown future and evolutionary processes of technological innovation. Thus, in the Kaleckian approach, it is the struggle for economic power that creates the cyclical path of economic activity. Courvisanos (1996) synthesises this alternative analysis by identifying susceptibility of investment as the sensitivity factor in the cyclical process. Courvisanos and Richardson (2008) is an exposition of a macroeconomic simulation model built by the authors along these Kaleckian lines to map out various types of traverses that emerge from different innovation and investment regimes.

A forerunner to the Kaleckian model set out in this paper is the business cycle model by Richard Goodwin, who also used the Lotka-Volterra modelling approach to identify the dynamic processes that developed out of the struggle over the distribution of income between workers and capitalists. The Goodwin (1967) model identifies workers as the predators with economic activity and employment as the prey, and the rate of unemployment acting "as a check upon worker's wage demands" (Keen, 2003, p. 179). This was an early attempt at complex systems modelling which develops models that are not required, and rarely do, converge to an equilibrium state. In this present modelling work, the ecological Lotka-Volterra model can be seen as a prequel to the integrative complexity modelling of the ecological system with the capital accumulation process. In this way, issues like the depletion and despoiling of the ecological system (e.g. oil spill in the Gulf of Mexico in May 2010) out of the needs of powerful capitalist forces (e.g. BP oil company) can be investigated together. It is only with the introduction of investment and the financial capital out of credit creation that a truly integrative approach has been made between ecology and economics.

In complexity modelling with adaptive feedback mechanisms over historical time the unit of analysis is functional cohorts that can be modelled based on the stylised facts. These facts portray both ecological and economic circumstances. From ecology there

is the functional variation in biodiversity of the ecosystem (Caron-Lormier, et al., 2009) that raises serious questions about any possibility of optimisation (Hooper et al., 2005; Meysman and Bruers, 2010). From economics, notable cohorts are industry clusters of firms and workers, government authorities, and supplying/purchasing agents outside the region being modelled. Instead of static equilibrium economic transactions the alternative is for modelling to operate in a time-dependent and uncertain world. Thus, complexity modelling is systems-based and time-dependent which allows for the incorporation of both elements in their reconstructed form and then using them for analysis and planning of sustainable development (Rosser, 1999).

Market production and transaction within a fragile global ecological system can be modelled with computer simulations to identify patterns of cohort behaviour. Then the way the system adapts and changes over time can be seen through changes in the variables (and in such ratios as the land degradation rate, profit rate and the capital-output ratio) over a succession of simulated historical short periods that can be represented as separate and discrete time periods. Courvisanos and Richardson (2006) use such a complexity modelling approach to trace out the path of investment decisions and their impact on the economy. More recently the same authors have embarked on building a sustainability model as a test bed for the evolution, investigation and trial simulations of a new synthesis of economics and ecology that does not have the limitations of the two conventional approaches described above (Richardson and Courvisanos, 2009). For this reason, this complexity approach to modelling aims to significantly enhance current efforts by policy makers, agriculturists and environmentalists to stave off a looming environmental disaster in places like the Murray-Darling river basin system and then build an ecologically supported economic system. In this way, a simulation exercise can be produced that provides a research focus for dealing with the interaction of economic and environmental changes. In the next section, this complexity modelling approach is applied to economic and ecological activity in a generic river basin as the prototype for a fully integrated ecological-economic model of the Murray-Darling basin.

The next section specifies the river basin model to show how adaptive complexity modelling can be used to fuse together the economic and ecological variables into computer simulation exercises. These model runs examine the impacts of using specific policy tools, which then can be evaluated iteratively as more information is gained on progress of the policy implementation. The development of such a modelling approach espoused in this paper also aims to have a spillover effect on the political element in that, if such a modelling process can be shown to be possible and effective, then governments and the public can become emboldened to push for needed political changes. The case study below centres on modelling water usage in a generic river basin and the need to develop mandatory water targets for sustainability.

The River Basin Model

This case study describes a generic ecological-economic River Basin Model that will be worked up during 2011 into a specific model of the Murray-Darling Basin, concentrating on the *economic* characteristics of that particular region. In the same year, the River Manager detailed *ecological* model of the MDB will become available. The plan is to integrate, at multiple entry-points, a greatly expanded version of the model outlined in this paper, shorn of its simplistic ecological content, with the

River Manager model. It is to this preliminary economic model of a river basin that we now focus on.

In 'year zero' (say, 1909) the river basin comprises a stock of arable land, that slowly degrades over a century of simulated historical time, due to water runoff from trend rainfall, exacerbated by soil erosion and fertiliser pollution from irrigation runoff, which also increases salinity by raising the water table. The MDB's actual and trend rainfall figures (1910-2009) are inserted for years one through 100. These reduce to 'useable rainfalls' after accounting for evapotranspiration losses. There is a conversion from rainfall in millimetres to supplies of water in ggalitres: actual for rainfed crops and potential for irrigated crops. Demands for irrigation water may be cut back by policy decisions, whenever irrigation allocations are set at less than 100% by a River Basin Commission (RBC) which administers the region. The RBC acts whenever a 'drought severity index anomaly' exceeds zero, indicating that actual drought severity (low rainfalls combined with high maximum and minimum temperatures) has risen above its trend.

Turning now to the river basin's economy, its land is equally suitable for growing crops of rainfed wheat or irrigated rice for *export* to the rest of Australia (RoA), though mainly to the rest of the world (RoW). Except for labour and irrigation water, all farm inputs, items of capital stock and consumer commodities (including milled rice and wheat flour) are sourced as *imports* from RoA/RoW. As the region issues no currency unit, its volatile balance of trade (exports minus imports) can have no impact on any inter-regional 'exchange rates'. These don't exist and, in any case, the river basin's RoW trade will hardly affect the Australian dollar's value, dominated as it is by mineral exports and financial flows related to Australia-RoW interest rate differences.

At this point we introduce the three-page Appendix A, a cut-down version of the Excel spreadsheet displaying the results of a model run with three ecological constraints binding. The constraints operate on formerly plentiful resources of (i) arable land, (ii) rain water, and (iii) irrigation water, when forced into scarcity during the closing years of a century of simulated historical time. (Specific carbon emission prices and caps have not yet been entered into the model.) The first three columns contain the names, symbols and growth rates of our model's variables, with bold underlined symbols for equation constants. The remaining columns are headed with the number of each simulated year. Years -1 and 0 are needed to insert initial values for those variables that need them. Then come Years 1 and 2, with Years 99 and 100 for comparison. Initial values are bold and underlined in the Years -1 and 0, as also are the RBC 'policy levers' and three real-world 'water resources' variables that have been copied into the model from the Murray-Darling Basin's climate history. All other data is computed from the equation or identity which underlies each cell of the spreadsheet and is responsible for the value appearing in that cell.

The supply of labour comes from the river basin's resident workforce, which experiences slow natural increase during the century. Some key equations are listed in Appendix B, e.g. in any given year, the money wage paid to fieldhands has four determinants. It cannot fall below the previous year's level, rises with both labour productivity and price inflation, and falls as the rate of unemployment increases, thus eroding the workers' bargaining power. The demand for workers is directly linked

with the total areas planted to rice and wheat and, as an emergent mathematical property, labour demand turns out to be inversely related to the wage. (In mainstream economics, this well-established relationship has to be stated, not awaited.) Employment of fieldhands periodically rises and falls because the area planted undergoes short-term cycles around an upward long-term growth trend as farms of minimum economic size (MES) are established, switched between crops or abandoned in accordance with the ‘economic outlooks’ envisaged by farmers, concerning their production of wheat and/or rice.

The simulated economic outlooks in Appendix A are characterised by a single number for each crop: its ‘profitability gap’ ($z\%$ pa), the difference between its ‘return on capital’ (expected profit rate) and its ‘cost of capital’ (market interest rate plus risk premium). Stemming from all its previous history, in year zero the region inherits a situation where the z for rice stands at 10.5% pa, while for wheat it is only 4.3% pa. Thus it is not surprising that in year one the area planted to rice expands by 2.4% whereas hectares under wheat rises by 1.6%. In fact, plantings increase whenever z is positive, decrease if z is negative and stays the same when z is zero.³

Area planted determines production of grains, whose export prices then fix each crop’s market value. Thus ‘crop-in-field’ investments by farmers are driven by the time series of profitability gaps, as too are their ‘land-and-water’ investments that maintain and improve farmland, together with all private irrigation infrastructure. (Public irrigation infrastructure is financed and built by Commonwealth and State governments, not by the RBC.) Farmers’ land-and-water investments, together with RBC expenditures on agricultural research, agronomy and extension, determine the fluctuating yields per hectare recorded when the river basin’s crops of wheat and rice are annually harvested. The key mathematical relationships in this computer model of the river basin economy are set out in Appendix B.

Model Results

Five model runs were conducted by Excel spreadsheet. The first run does not have any ecological constraints and represents the ‘business-as-usual’ base case where no natural constraints bite and there are no RBC policy changes. The next run was only land constrained, followed by only rain water constrained, and only irrigation water constrained model runs. The fifth run was fully constrained and is the one set out in Appendix A. Some of the more significant results of the simulation exercise portrayed there are set out in this section, which makes comparisons with the unconstrained model run where appropriate.

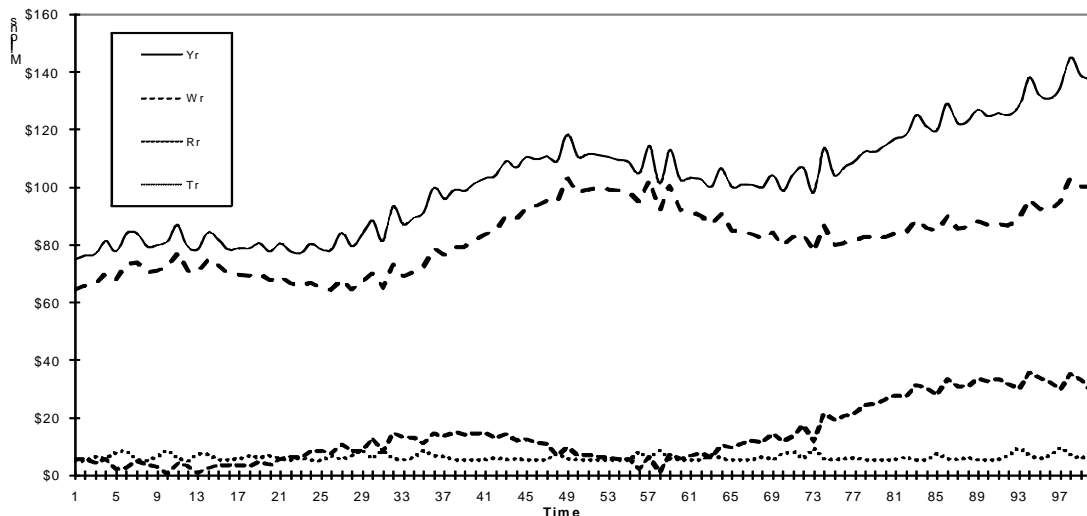
Figure 1 displays the economic variables that are the outcome of crop production. Recalling that ‘economic outlooks’ – profitability gaps – determine investment and production, hence also the region’s real gross domestic product (GDP), the first results show how this model economy undergoes business cycles rather than smooth economic growth. Focusing on real GDP (Yr), there are two major troughs, one at Year 23 (\$77m.) and the other at Year 73 (\$98m.), producing a 50 year cycle. There are three major cycle peaks: Year 11 (\$87m.) – not bettered until Year 30, Year 49

³ Whenever these crops’ combined demand for land exceeds the hectares available, farmers anticipating the higher z for rice will outbid the low- z wheat growers and secure all the land they want, leaving the residual area planted to wheat, the crop with lower expected profitability.

(\$118m.) – not bettered until Year 82, then the final peak at Year 98 (\$145m.). Peak-to-peak cycles are 38 and 49 years respectively. There is no significant difference in cycle amplitude between the two cycle peaks, thus volatility of Yr is roughly constant.

The cycle pattern of Yr comprises the economy’s wages bill (Wr), gross operating surplus or gross profits (Rr) and taxation receipts (Tr), all adjusted for price inflation. Wages is the largest component of GDP, but from the Kaleckian theory, it is profits that drive real investment (Ir). Thus, the rise in Rr from \$13.5m (Year 71) to \$17.5m. (Year 72), and then followed by strong rise in Year 74 to \$21.1m., provides the impetus for investment (with Ir spending in Year 74 at a nearly \$10m., which is about double the average of the previous ten years) to drag the economy out of the trough. The peak of Rr in Year 94 (\$35.5m.) precedes the Year 98 cycle peak; and the decrease in profits from this peak leads to a collapse of Ir (-\$111,158) in Year 95 to usher in the end of century downturn. If the simulation continued beyond Year 100, the Rr cycle would reach its trough, then move into a new upswing phase, drawing Yr and Wr along in its wake. It is interesting to note that the wages component in the fully constrained model in Year 100 reaches \$100m., whereas in the completely unconstrained model run, wages in this same year are \$141m.. Thus, profits (Rr) are lower by \$2.3m. in Year 100 for the unconstrained model run. The explanation for this is provided below when further data from the model runs are examined.

Figure 1. Real Gross Domestic Product & its Income Components



Contra neoclassical economic thought, these model cycles are *endogenous*, with exogenous shocks like unexpected changes in the world oil price, interest and exchange rates, prices of exports and imports, government expenditures, and shifts in consumers’ tastes and preferences playing only a secondary role. Small irregularities in the otherwise smooth cycles of Figure 1 are caused by exogenous rainfall and temperature shocks to realised profitability. The economic outlook for farmers is always uncertain, not merely risk-laden. Econometric studies strongly suggest that the most recent realised financial results of business decision-makers tend to loom largest in their minds as they develop their expectations of future sales and cost factors, hence also their ‘economic outlooks’ concerning the profitability of next year’s outlays on capital assets. Because of these considerations, and to keep things simple, this simulation model assumes a basic ‘static expectations function’ for profitability outlooks; this year’s profit rate is expected to be the same as last year’s realised profit rate. With the market interest rate and crop-specific risk premium both known, each

crop's *expected* profitability gap is set equal to the profit rate it *realised* after last year's harvest ($z\%$ pa).

Farmers are forever realising financial results, both good and bad, that they never expected. They can and must develop expectations of earning a certain profit rate, yet have no control over their realised profitability. The latter depends on a host of influences: export prices for rice and wheat, crop yields that fluctuate, RBC decisions over irrigation allocations and the price of this water, changing labour productivities and wages, the domestic prices of fertiliser and seeds, rentals for using fixed assets (all imported), and so on. Recall that in Year 0 the rice profitability gap (z_r) stands at 10.5% pa, causing a rise in investment. However, that is followed by gaps of 9.7, 9.1, 4.2, ... % pa, causing ever-smaller increases in the area planted to rice. Similarly, the wheat profitability gap (z_w) starts out at 4.3% pa, but is followed by gaps of 3.2, 2.7, 2.1, ... % pa, which also ameliorates the business cycle's upswing for that product. Figure 2 shows what happens.

In Figure 2, the dark dashed curve displays how many hectares are planted to irrigated rice in any particular year (A_r), and the dark dotted curve indicates the same for rainfed wheat (A_w). The extent of the fixed arable land planted (or utilised) pa for wheat and rice is shown as A . Two points of interest arise. One is that A_w and A_r fluctuate, which then reflects on total production (Y_r), as in Figure 1. The second is that when land utilisation (A) reaches full arable capacity (A_U) in Year 82, rainfed rice crop planting begins to decrease and then lose its 80-odd year domination of irrigated wheat crop planting in relation to the total land utilised. It is land scarcity that makes the non-irrigated crop the much more strongly favoured of the two.

Figure 2. Land Endowment & Area Planted (hectares)

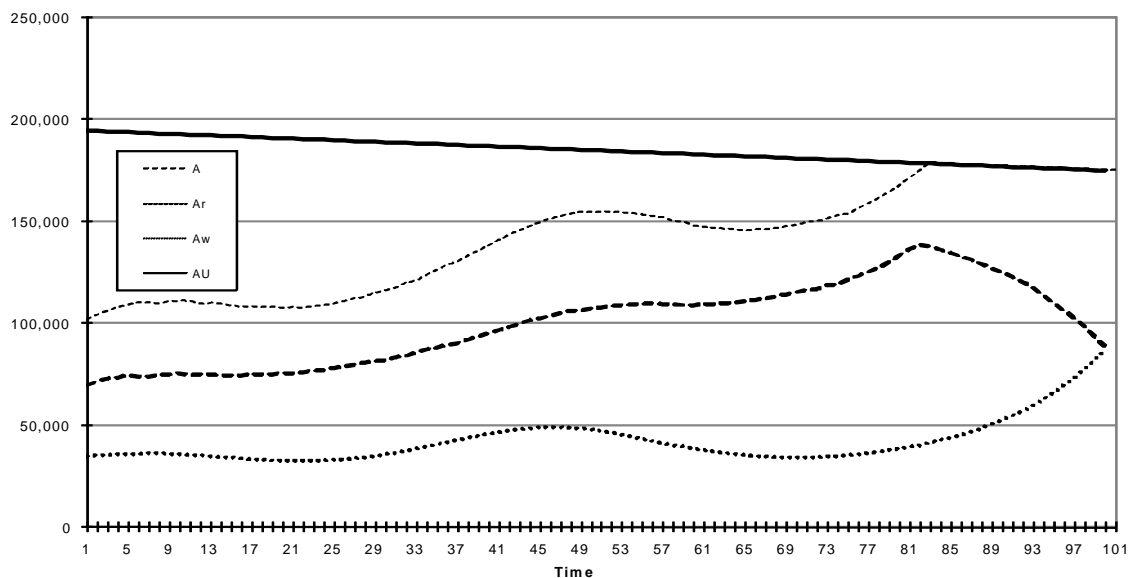
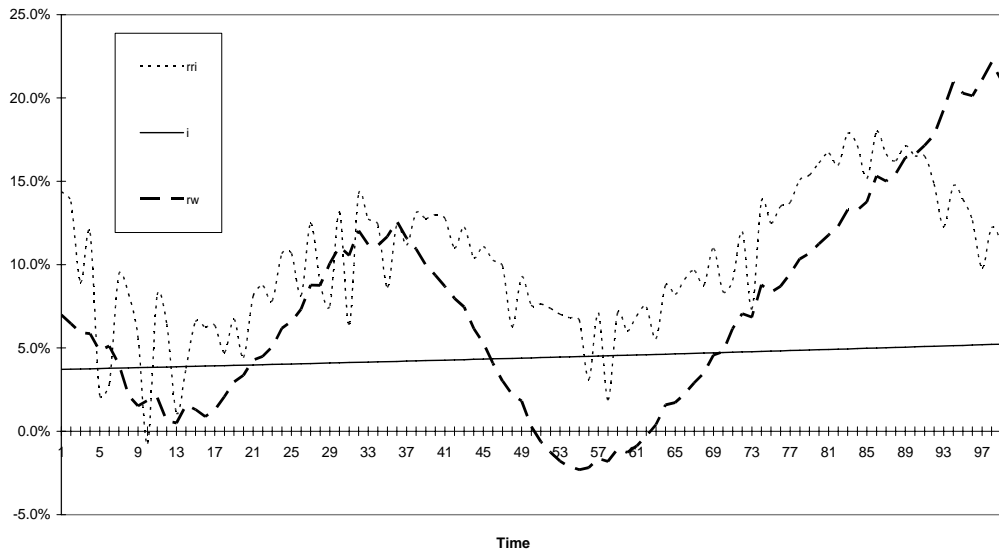


Figure 3 reflects the cyclical effects identified in Figure 1, in terms of the realised profit rates for rice and wheat. The volatility and amplitude of these profit rates, as seen by the sequence of profitability gaps between the two crops' cycling profit rates and the relatively stable interest rate ($i\%$ pa), adjusted for risk, drive real investment and the business cycle. Three significant points arise here. First, on a year-by-year

basis, rri is much more volatile than rw due to the host of exogenous influences that impact on irrigated crops much more than non-irrigated crops, especially RBC decisions over irrigation allocations and the price of water. Second, the amplitude of the smoothed longer-term profit rate cycle of irrigated rice (rri% pa) is lower than that of rainfed wheat (rw% pa) due to (a) rice farmers reacting less than wheat farmers to profitability gaps due to their greater volatility in the short-term and (b) the RBC's water 'taxation' of rice production. The tax-reduced profitability of rice lowers its profitability gap relative to that of wheat, thus ameliorating the former crop's cycles.

Figure 3. Interest & Profit Rates

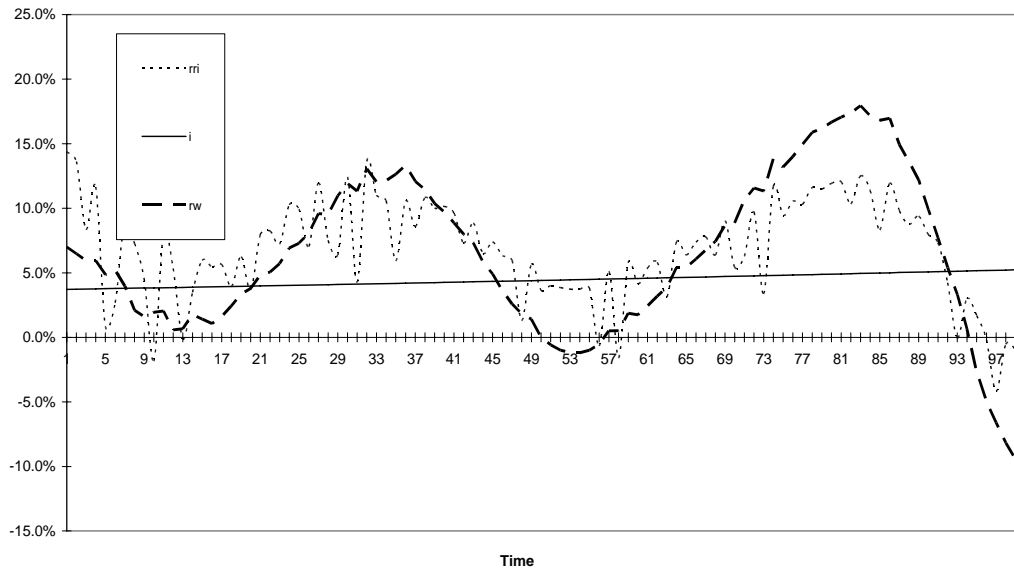


The third significant point relates back to Figure 1 and the relative pattern of rice and wheat production over the simulated century. Figure 3 shows clearly how the land endowment constraint, when it is reached in Year 82, limits the expansion of irrigated rice, to the detriment of its profit rate compared to the rainfed wheat which shows continual rise in its profit rate, even with the onset of the economic downturn in Year 98. This sharp distinction can be noted even further with Figure 4, which shows profit rates from the completely unconstrained model run. In this graph, the dominance of rice is challenged by wheat as land utilisation reaches 191,472 ha in Year 92 when land endowment is 196,101 ha, however that challenge is weakened when the downturn reduces land utilisation and allows rice to widen the production gap. The source of the problem is the collapse of both profit rates in Figure 4, to bring about a much more severe downturn in the unconstrained model run. This much stronger synchronisation of profit rate cycles in Figure 4 is due to the steep rise of the real wage from Year 83. It is in that year in the unconstrained model run that the real GDP per workforce member rises above the real labour productivity, causing steep real wage increases and the onset of a strong drop in both profit rates and a deep cyclical downturn.

The final results to note are the river basin ecology variables in Appendix A. The ecological outcomes are the basis upon which the economic circumstances described above manifest themselves. The fully constrained model run shows over the century a reduction in actual rainfall and useable rainfall. This has an impact on the way that the RBC acts via the drought severity index anomaly. The model run shows that the index anomaly began at -9.59% indicating that the combined rainfall/temperature conditions

were such that drought severity was well below trend and thus not a concern. A century later, the index anomaly of 25.6% exceeds zero by a great deal, as low rainfall and high maximum and minimum temperatures push the measure well above trend. The last yearly negative index anomaly occurs in Year 91, with Years 93 and 97 registering well above 40%. As a result the RBC raises their water price ‘taxation rate’ and reduces the irrigation water allocation. This only worsens the downturn which had already begun due to the land constraint, as discussed above.

Figure 4. Unconstrained Interest & Profit Rates



Implications

There are at least two policy implications that may be drawn from the results of exercising even this simple dynamic, non-equilibrium, non-optimising (in short, non-mainstream) and profitability-driven simulation model of our regulated river basin’s ecology and economy. First, experimental simulation runs, in which the land and rainfall constraints are forced to bind, indicate that rainfed crops benefit from increased scarcity *vis-à-vis* irrigated crops. This raises the problem of whether to retire the massive past investments in public and private irrigation infrastructure in Australia, plus the protection and subsidies provided to irrigated crops like rice and cotton. A case in point concerns the world’s largest cotton plantation on one of the biggest private irrigation projects in the world. Cubbie Station is located in the north of the MDB on a Queensland river that feeds into the Darling and, ultimately, the Murray. Past irrigation infrastructure investments (plus dependent business enterprises) create dilemmas about using the station’s water entitlements for reviving the fortunes of long-established irrigation farmers downstream of Cubbie, or instead reviving the MDB’s ecosystem. Irrigation farmers below Cubbie (in New South Wales, Victoria and South Australia) are being denied benefit of the water, but if the government buys the Cubbie entitlements and retires them for the benefit of the ecosystem, then the below-Cubbie farmers will still be no better off.⁴

⁴ Cubbie Station property is Australia’s biggest cotton plantation with a total land holding of 93,000 hectares. However, the station’s permits to divert and store more than 500,000 megalitres of water (enough to fill Sydney Harbour) upset downstream MDB users. Coming under financial pressure, Cubbie which is valued at \$450m., went into voluntary administration on 30 October 2009.

Secondly, constrained and unconstrained experimental simulation runs show that there is a difference in economic outcomes. When the RBC raises their water price ‘taxation rate’ in response to droughts and reduces water allocations, this helps *ameliorate* business cycle volatility over the long term. Such reductions in the volatility of investment, profitability (hence lower risk premia) and output may actually *benefit* irrigation farmers, provided their average financial return on capital remains above their new, lower, average opportunity cost of capital. Here is an example of tax-funded water sustainability measures being consistent with the continuing sustainable profitability of irrigated agriculture. This important issue is reflected in simulation experiments by less severe troughs in recessions for the irrigated crop. The implications from this provide support for policy intervention due to systemic failure in the economic system as a result of ecological pressures (Courvisanos, 2009).

The above policy implications are only tentative, given the exploratory nature of this simplistic model. However, the River Basin Model nonetheless captures some of the complex feedbacks and other interactions within and between the ecology and economy of a generic regulated river basin.

Conclusion

The simulation exercises show that it is possible to integrate a demand-based economic model with a supply-based two-crop river basin land-use model. This provides confidence to proceed with the actual task of integrating a similar (but multi-cropping) non-equilibrium ecology-economy complexity model with the already-specified River Manager/River Operator ecological Murray-Darling Basin model.

Testing out the simulation model iterations, both constrained and unconstrained, conveys an understanding of the nature and viability of the regulated river basin model, from both the model-building and political economy perspectives. The ability to unite a supply-based ecological model with a demand-based economic model provides strong encouragement for further research into this modelling approach that has ecological constraints incorporated into a dynamic non-equilibrium macroeconomic model equipped with multiple agricultural industries.

The next iteration of the model will add more crops to the model, including a ‘crop of last resort’ (rainfed fodder). Once a proof-of-concept model is successfully developed, a joint research project involving the Universities of Sydney and Ballarat, plus Imperial College London, will develop and test an integrated Economic and Ecological Sustainability Model for the Murray-Darling Basin (EESM:MDB). The focus of this collaboration will be on the interactions between agribusiness, changes in land use, energy usage, carbon emissions, and water consumption, given various climate change scenarios. Such a research agenda has a strong political economy focus related to better economic policy developments that are in step with ecological concerns.

Queensland’s Natural Resources Minister, Stephen Robertson, argued that the Federal Government should buy Cubbie and retire its water entitlements for the benefit of the environment, but the Federal Government refused (ABC, News 2009).

Finally, two observations can be made from the perspective of pure economic theory development. One is that the current general equilibrium modelling approaches to ecological-economic integration are inadequate, and for the same reasons that post Keynesians have for a long time criticised the mainstream's macroeconomic theories, underpinned by the Walrasian general equilibrium model. This paper has attempted to show what can be done by combining the recent complexity-based work of ecologists with complexity modelling of the type conducted by the present authors in previous research work. The other observation is that Lotka-Volterra biological models of predator-prey dynamics have similarities with the type of ecologically constrained profit-based economic cycles shown in this paper. Much needs to be done in this area, and urgently, if the devastation of the ecosystem is not arrested and reversed so that the climate change global target of 350 parts per million global carbon emissions and resource integrity are achieved (Rockström, 2009).

References

- ABC News (2009), 'Water-sucking Cubbie Station for sale' and 'Cubbie Station going into administration', accessed 23 November 2009.
<http://www.abc.net.au/news/stories/2009/08/17/2657448.htm>, and
<http://www.abc.net.au/news/stories/2009/10/29/2727856.htm> (respectively).
- Amir S. (1979), "Economic Interpretations of Equilibrium Concepts in Ecological Systems", *Journal of Social and Biological Structures*, Vol 2 (4), 293–314.
- Caron-Lormier, G., *et al.* (2009), "How might we model an ecosystem?", *Ecol. Model.*, Vol. 220, pp. 1935-1949.
- Collis, B. (2002), *Fields of Discovery: Australia's CSIRO*, Crows Nest, NSW: Allen & Unwin.
- Costanza, R. and Daly, H. (1987), "Toward an ecological economics", *Ecol. Model.* Vol. 38, pp. 1–7.
- Courvisanos, J. (1996) *Investment Cycles in Capitalist Economies: A Kaleckian Behavioural Contribution*, Cheltenham: Edward Elgar.
- Courvisanos, J., (2009), "Optimise Versus Satisfice: Two Approaches to an Investment Policy for Sustainable Development", in Holt, R., Pressman, S. and Spash, C.L. (eds.), *Post Keynesian and Ecological Economics: Confronting Environmental Issues*, Cheltenham, UK and Northampton, US: Edward Elgar, 2009, pp. 279-300.
- Courvisanos, J. and Richardson, C. (2006), "Corridor of Viability: Complexity Analysis for Enterprise and Investment", in Setterfield M. (ed), *Complexity, Endogenous Money and Macroeconomic Theory: Essays in Honour of Basil J Moore*, Cheltenham, UK: Edward Elgar, pp. 99-118.
- Courvisanos, J. and Richardson, C. (2008), 'Invention, Innovation, Investment: Heterodox simulation modeling of capital accumulation', in Harvey, J. and Garnett Jr., R. (eds), *Future Directions for Heterodox Economics*, The University of Michigan Press, Ann Arbor, pp. 185-221.
- Finnoff and Tschirhart (2008), "Linking dynamic ecological and economic general equilibrium models", *Resour. Energy Econ.*, Vol 30, pp. 91–114.
- Garnaut, R. (2008a), *Garnaut Climate Change Review: Interim Report to the Commonwealth, State and Territories Governments of Australia*, Melbourne: Victorian Department of Premier and Cabinet, February. Access at: www.garnautreview.org.au
- Garnaut, R. (2008b), *The Garnaut Climate Change Review: Final Report*, Cambridge University Press, Port Melbourne.
- Goodwin, R.M. (1967), "A Growth Cycle", in Feinstein, C. H. (ed.) *Socialism, Capitalism and Economic Growth*, Cambridge: Cambridge University Press.

- Hameed, T. and Podger, G. (2001), “Use of the IQQM Simulation Model for Planning and Management of a Regulated River System”, in Mariño, M. and Simonovic, S. (eds), *Integrated Water Resources Management*, IAHS Press, Wallingford, pp. 83-9.
- Hollis, M. and Nell, E. (1975), *Rational Economic Man*, Cambridge: Cambridge University Press.
- Hooper, D. U., *et al.* (2005) “Effects of biodiversity on ecosystem functioning: A consensus of current knowledge”, *Ecol. Monogr.* Vol. 75, pp. 3-35.
- Jackson, T. (2009), *Prosperity without Growth? The Transition to a Sustainable Economy*, London: Sustainable Development Commission.
- Kalecki, M. (1939), *Essays in the Theory of Economic Fluctuations*, Allen & Unwin, London. Reprinted in Osiatyński, J. (ed.) (1990), *Collected Works of Michal Kalecki, Volume I: Capitalism – Business Cycles and Full Employment*, Clarendon Press, Oxford, pp. 233-318.
- Keen, S. (2003), “Growth Theory”, in King, J. E. (ed.), *The Elgar Companion to Post Keynesian Economics*, Cheltenham, UK: Edward Elgar, pp. 175-80.
- Lotka A.J. (1925), *Elements of Physical Biology*, Baltimore, MD: Williams & Wilkins.
- Meysman, F. J. R. and S. Bruers (2010), “Ecosystem functioning and maximum entropy production: a quantitative test of hypotheses”, *Philos. Trans. R. Soc. B-Biol. Sci.*, Vol 365, pp. 1405.
- Perrings C. (1987), *Economy and Environment*, Cambridge: Cambridge University Press
- Podger, G., Davidson, A. and Yang, A. (2008), “A Framework to Support the Modelling of Surface and Ground Water Resources throughout the Murray-Darling Basin”, in Lambert, M., Daniell, T. and Leonard, M. (eds), *Proceedings of Water Down Under 2008*, Engineers Australia: Causal Productions, Modbury [CD-Rom] accessed 13 March 2010.
<http://search.informit.com.au/browsePublication;isbn=0858257351;res=IELENG>
- Richardson, C. and Courvisanos, J. (2009), “Towards a post-Keynesian model of agricultural production in a regulated river basin”, paper presented at the Eight Australian Society of Heterodox Economists (SHE) Conference, University of New South Wales, Sydney, 7-8 December.
- Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin III, F.S., Lambin, E., Lenton, T., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., de Wit, C., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R., Fabry, V., Hansen, J.,

- Walker, B., Liverman, D., Richardson, K., Crutzen, P. and Foley, J. (2009), “A Safe Operating Space for Humanity”, *Nature*, No. 461, pp. 472-5.
- Rosser Jr. J. B., (1999), “On the Complexities of Complex Economic Dynamics”, *The Journal of Economic Perspectives*, Vol. 13 (4), pp. 169-192
- Runde, J. (1991), “Keynesian Uncertainty and the Instability of Beliefs”, *Review of Political Economy*, Vol 3 (2), pp. 125-45.
- Simons, M., Podger, G. and Cooke, R. (1996), “IQQM - A Hydrologic Modelling Tool for Water Resource and Salinity Management”, *Environmental Software*, Vol 11 (1-3), pp. 185-92.
- Tschirhart, J. (2009), “Integrated Ecological-Economic Models”, *Annual Review of Resource Economics*, Vol. 1, pp. 381-407
- Volterra V. (1926), “Fluctuations in the abundance of a species considered mathematically”, *Nature*, Vol. 118, pp. 558–60.
- Wätzold, F., Drechsler, M., Armstrong, C., Baumgärtner, S., Grimm V. (2006), “Ecological-economic Modeling for Biodiversity Management: Potential, Pitfalls, and Prospects”, *Conservation Biology*, Vol. 20 (4), 1034–41.
- Welsh, W. and Podger, G. (2008), Australian Hydrological Modelling Initiative: River System Management Tool (AHMI: RSMT) functionality specifications, *eWater Technical Report*, eWater Cooperative Research Centre, Canberra.
- Young, W., Podger, G., Walker, G. and Chiew, F. (2008), “Integrated Assessment of the Likely Impacts of Climate Change and Future Developments on Water Availability and Use in the Murray-Darling Basin”, in Lambert, M., Daniell, T. and Leonard, M. (eds), *Proceedings of Water Down Under 2008*, Engineers Australia: Causal Productions, Modbury, pp. 1948-56 [CD-Rom] accessed 13 March 2010.
<http://search.informit.com.au/browsePublication;isbn=0858257351;res=IELENG>

Appendix A – Model Run with All Constraints Binding: Start and End of the Simulated Century

GENERIC RIVER BASIN MODEL	sn	gr	-1	0	1	2	...	99	100
<u>IRRIGATED RICE SUB-MODEL</u>									
Constants (aka Parameters)									
Rice Reaction Coefficient	<u>or</u>	0.00%		0.2294	0.2294	0.2294	...	0.2294	0.2294
Rice Seedling Rate (kg/ha)	<u>asr</u>	0.00%		20	20	20	...	20	20
Rice Fertiliser Rate (kg/ha)	<u>ufr</u>	0.00%		100	100	100	...	100	100
Rice Water Rate (Ml/ha)	<u>ahr</u>	0.00%		2.5	2.5	2.5	...	2.5	2.5
Rice Emissions Rate (kg/ha)	<u>agr</u>	na		0.0	0.0	0.0	...	0.0	0.0
Rice Crop Yield Coefficient	<u>br</u>	0.00%		0.1	0.1	0.1	...	0.1	0.1
Rice Farm MES (ha)	<u>lr</u>	0.00%		3,000	3,000	3,000	...	3,000	3,000
Rice Risk Premium	<u>wr</u>	0.00%		1.0%	1.0%	1.0%	...	1.0%	1.0%
Resources and Utilisation									
Ideal Rice Area Planted (ha)	Ari	1.00%	67,299	67,896	69,538	71,078	...	198,278	200,562
Actual Rice Area Planted (ha)	Ar	0.63%	67,299	67,896	69,538	71,078	...	93,048	88,153
Rice Number of MES Farms	Mr	0.62%	23	23	24	24	...	32	30
Rice Water Applied (Gl)	Hr	0.06%	172	170	172	172	...	184	192
Rice LP (t/worker pa)	qr	0.50%		10.0	10.1	10.1	...	16.4	16.5
Rice LP Growth (% pa)	gqr	0.00%		0.5%	0.5%	0.5%	...	0.5%	0.5%
Rice Employment (workers)	Lr	0.16%		22,612	22,710	23,119	...	19,591	18,252
Rice Crop Yield Investments	Bir	0.79%		\$6,360,779	\$6,368,259	\$6,507,194	...	\$15,222,115	\$18,928,581
Rice Crop Yield Growth (% pa)	gbr	na		0.5%	-0.6%	1.5%	...	-13.4%	23.6%
Rice Crop Yield (t/ha)	br	0.00%		3.36	3.36	3.36	...	3.28	3.23
Production, Inputs, Prices									
Rice Produced (t)	Qr	0.66%		226,120	228,239	233,506	...	320,996	300,558
Rice Seed Sown (t)	Ssr	0.63%	1,369	1,358	1,391	1,422	...	1,861	1,763
Rice Fertiliser Applied (t)	Fr	0.63%	6,837	6,790	6,954	7,108	...	9,305	8,815
Rice Carbon Emissions (t)	Gr	na		0	0	0	...	0	0
Rice Export Price (\$/t)	Pr	0.60%	\$235	\$236	\$236	\$238	...	\$425	\$427
Rice Seedling Price (\$/t)	Psr	0.70%		\$1,400	\$1,410	\$1,420	...	\$2,793	\$2,812
Rice Fertiliser Price (\$/t)	Pfr	0.70%		\$1,000	\$1,007	\$1,014	...	\$1,995	\$2,009
Rice Fixed Asset Rentals (\$/farm)	Pkr	0.70%		\$50,000	\$50,350	\$50,702	...	\$99,744	\$100,442
Rice Wage Bill	Wbr	0.98%		\$34,144,160	\$34,665,198	\$35,709,447	...	\$66,832,288	\$63,060,588
Rice Seed Bill	Sbr	1.36%		\$1,916,565	\$1,914,392	\$1,974,408	...	\$5,472,586	\$5,233,739
Rice Fertiliser Bill	Fbr	1.36%		\$6,837,071	\$6,837,113	\$7,051,457	...	\$19,544,950	\$18,691,926
Rice Fixed Asset Rentals Bill	Kbr	1.35%		\$1,150,000	\$1,158,050	\$1,216,859	...	\$3,291,558	\$3,214,157
Rice Water Bill	Hbr	0.74%		\$5,149,641	\$5,127,835	\$5,239,289	...	\$11,685,200	\$15,350,920
Rice Emissions Bill	Gbr	na		\$0	\$0	\$0	...	\$0	\$0
Rice Total Cost	CTr	1.14%		\$50,502,406	\$51,088,967	\$52,670,984	...	\$123,152,341	\$121,902,851
Rice Average Cost	CAr	0.48%		\$223.34	\$223.84	\$225.57	...	\$383.66	\$405.59
Rice Prime Cost	CPr	0.38%		\$217.57	\$217.77	\$219.23	...	\$332.80	\$351.18
Rice Margin	mnr	na		\$18.71	\$18.52	\$18.47	...	\$91.86	\$76.02
Rice Markup	mr	na		0.086	0.085	0.084	...	0.276	0.216
Capital, Profits, Debt, Equity									
Rice Crop-in-Field Asset	Kr1	1.26%	\$25,864,928	\$26,554,162	\$26,964,809	\$27,586,963	...	\$67,750,161	\$63,817,071
Rice Crop-in-Field Investment	Ir1	na		\$689,235	\$410,647	\$622,154	...	-\$5,872,192	-\$3,933,090
Rice Land&Water Investment	Ir2	1.00%		\$1,211,138	\$1,240,425	\$1,267,905	...	\$3,536,915	\$3,577,661
Rice Land&Water Asset	Kr2	3.19%		\$1,211,138	\$2,451,563	\$3,719,468	...	\$194,340,896	\$197,918,557
Rice Farms Asset	Kr	2.16%	\$26,940,438	\$27,765,301	\$29,416,372	\$31,306,431	...	\$262,091,057	\$261,735,629
Rice Farms Investment	Ir	na		\$824,863	\$1,651,071	\$1,890,059	...	-\$2,335,277	-\$355,429
Rice Sales Revenue	SRr	1.26%		\$53,428,898	\$53,929,618	\$55,504,969	...	\$136,313,324	\$128,399,947
Rice Variable Cost	VCr	1.04%		\$49,197,437	\$49,702,588	\$51,191,460	...	\$106,826,582	\$105,551,330
Rice Profit	Rri	na		\$4,231,461	\$4,227,030	\$4,313,509	...	\$29,486,742	\$22,848,617
Rice Interest Bill	Jbr	1.33%		\$927,564	\$929,184	\$960,715	...	\$2,678,079	\$2,673,276
Rice Profit less Interest Bill	Rnr	na	\$1,000,000	\$3,303,898	\$3,297,846	\$3,352,794	...	\$26,808,662	\$20,175,341
Rice Profit Rate (% pa)	rrr	na		15.2%	14.4%	13.8%	...	11.3%	8.7%
Rice Normal Profit Rate (% pa)	nr	0.29%		4.7%	4.7%	4.7%	...	6.2%	6.2%
Rice Profitability Gap (% pa)	zr	na	3.9%	10.5%	9.7%	9.1%	...	5.0%	2.5%
Rice Average Debt	Dr	0.97%		\$25,069,288	\$25,025,480	\$25,784,473	...	\$51,215,501	\$50,945,326
Rice Average Equity	Er	3.20%		\$2,696,013	\$4,390,892	\$5,521,958	...	\$210,875,557	\$210,790,302
Rice Debt:Equity Ratio	dr	2.15%		9.299	5.699	4.669	...	0.243	0.242
<u>RAINFED WHEAT SUB-MODEL</u>									
Constants (aka Parameters)									
Wheat Reaction Coefficient	<u>ow</u>	0.00%		0.3600	0.3600	0.3600	...	0.3600	0.3600
Wheat Seed Rate (kg/ha)	<u>osw</u>	0.00%		150	150	150	...	150	150
Wheat Fertiliser Rate (kg/ha)	<u>ofw</u>	0.00%		80	80	80	...	80	80
Wheat Water Rate (Ml/ha)	<u>ohw</u>	0.00%		1.4	1.4	1.4	...	1.4	1.4
Wheat Emissions Rate (kg/ha)	<u>ogw</u>	na		0.0	0.0	0.0	...	0.0	0.0
Wheat Crop Yield Coefficient	<u>bw</u>	0.00%		0.2	0.2	0.2	...	0.2	0.2
Wheat Farm MES (ha)	<u>lw</u>	0.00%		1,400	1,400	1,400	...	1,400	1,400
Wheat Risk Premium (% pa)	<u>pw</u>	0.00%		0.05%	0.05%	0.05%	...	0.05%	0.05%
Resources and Utilisation									
Ideal Wheat Area Planted (ha)	Aw1	0.46%	34,029	34,152	34,684	35,086	...	82,471	87,164
Actual Wheat Area Planted (ha)	Aw	0.46%	34,029	34,152	34,684	35,086	...	82,471	87,164

Wheat Number of MES Farms	Mw	0.46%	<u>25</u>	25	25	26	...	59	63
Wheat Water Applied (Gl)	Hw	0.46%		48	49	49	...	115	122
Wheat Water Scarcity Index	hsw	0.40%		0.3179	0.3021	0.3098	...	0.8188	0.9026
Wheat LP (t/worker pa)	qw	0.50%		<u>5.0</u>	5.0	5.1	...	8.2	8.2
Wheat LP Growth (% pa)	gqw	0.00%		<u>0.5%</u>	0.5%	0.5%	...	0.5%	0.5%
Wheat Employment (workers)	Lw	0.23%		19,669	19,724	19,895	...	38,974	39,917
Wheat Crop Yield Investments	Blw	0.72%		\$5,774,641	\$5,762,571	\$5,881,390	...	\$13,194,476	\$16,946,080
Wheat Crop Yield Growth (% pa)	gbw	na		<u>2.1%</u>	-0.9%	1.4%	...	-14.8%	27.7%
Wheat Crop Yield (t/ha)	bw	0.30%		<u>2.89</u>	2.90	2.90	...	4.11	3.99
Production, Inputs, Prices									
Wheat Produced (t)	Qw	0.74%		98,344	99,113	100,474	...	319,294	328,649
Wheat Seed Sown (t)	Ssw	0.46%	<u>5,139</u>	5,123	5,203	5,263	...	12,371	13,075
Wheat Fertiliser Applied (t)	Fw	0.46%	<u>2,741</u>	2,732	2,775	2,807	...	6,598	6,973
Wheat Carbon Emissions (t)	Gw	na		0	0	0	...	0	0
Wheat Export Price (\$/t)	Pw	0.50%	\$368	<u>\$370</u>	\$370	\$372	...	\$603	\$606
Wheat Seed Price (\$/t)	Psw	0.70%	\$440	<u>\$435</u>	\$438	\$441	...	\$868	\$874
Wheat Fertiliser Price (\$/t)	Pfw	0.70%		<u>\$890</u>	\$896	\$903	...	\$1,775	\$1,788
Wheat Fixed Asset Rentals (\$/farm)	Pkw	0.70%		<u>\$20,000</u>	\$20,140	\$20,281	...	\$39,898	\$40,177
Wheat Wage Bill	Wbw	1.06%		\$29,700,017	\$30,106,738	\$30,730,477	...	\$132,955,773	\$137,908,838
Wheat Seed Bill	Sbw	1.13%		\$2,235,464	\$2,243,998	\$2,294,907	...	\$10,119,986	\$10,810,082
Wheat Fertiliser Bill	Fbw	1.13%		\$2,439,311	\$2,448,624	\$2,504,174	...	\$11,042,805	\$11,795,829
Wheat Fixed Asset Rentals Bill	Kbw	1.12%		\$500,000	\$503,500	\$507,025	...	\$2,234,270	\$2,370,441
Wheat Emissions Bill	Gbw	na		\$0	\$0	\$0	...	\$0	\$0
Wheat Total Cost	CTw	1.12%		\$35,577,082	\$36,040,234	\$36,810,254	...	\$165,428,787	\$172,251,960
Wheat Average Cost	CAw	0.38%		\$361.76	\$363.63	\$366.37	...	\$518.11	\$524.12
Wheat Prime Cost	CPw	0.33%		\$354.62	\$356.19	\$358.67	...	\$489.68	\$495.62
Wheat Margin	mnw	na		\$15.38	\$13.81	\$13.18	...	\$113.54	\$110.62
Wheat Markup	mw	na		0.043	0.039	0.037	...	0.232	0.223
Capital, Profits, Debt, Equity									
Wheat Crop-in-Field Asset	Kw1	1.24%	<u>\$18,036,474</u>	\$18,102,750	\$18,335,905	\$18,587,674	...	\$95,823,065	\$99,123,787
Wheat Crop-in-Field Investment	Iw1	na		\$66,276	\$233,155	\$251,769	...	\$1,052,232	\$3,300,723
Wheat Land Investment	Iw2	0.46%		<u>\$625,000</u>	\$634,736	\$642,101	...	\$1,509,277	\$1,595,161
Wheat Land Asset	Kw2	2.91%		\$625,000	\$1,259,736	\$1,901,836	...	\$76,101,240	\$77,696,401
Wheat Farms Asset	Kw	1.86%	<u>\$18,610,477</u>	\$18,727,750	\$19,595,641	\$20,489,511	...	\$171,924,305	\$176,820,189
Wheat Farms Investment	Iw	na		\$117,273	\$867,891	\$893,870	...	\$2,561,509	\$4,895,884
Wheat Sales Revenue	SRw	1.24%		\$36,387,438	\$36,671,810	\$37,361,226	...	\$192,604,360	\$199,238,813
Wheat Variable Cost	VCw	1.07%		\$34,874,791	\$35,302,860	\$36,036,582	...	\$156,352,833	\$162,885,189
Wheat Profit	Rw	na		\$1,512,647	\$1,368,950	\$1,324,644	...	\$36,251,527	\$36,353,624
Wheat Interest Bill	Jbw	1.37%		\$655,248	\$662,875	\$679,762	...	\$3,889,552	\$4,086,174
Wheat Profit less Interest Bill	Rnw	na	<u>\$300,000</u>	\$857,399	\$706,076	\$644,882	...	\$32,361,974	\$32,267,449
Wheat Profit Rate (% pa)	rw	na		8.1%	7.0%	6.5%	...	21.1%	20.6%
Wheat Normal Profit Rate (% pa)	nw	0.35%		3.8%	3.8%	3.8%	...	5.3%	5.3%
Wheat Profitability Gap (% pa)	zw	na	<u>1.0%</u>	4.3%	3.2%	2.7%	...	15.8%	15.3%
Wheat Average Debt	Dw	1.01%		\$17,709,396	\$17,853,049	\$18,244,021	...	\$74,383,666	\$77,871,308
Wheat Average Equity	Ew	3.04%		\$1,018,355	\$1,742,592	\$2,245,490	...	\$97,540,639	\$98,948,880
Wheat Debt:Equity Ratio	dw	1.96%		17.390	10.245	8.125	...	0.763	0.787
<u>RIVER BASIN ECOLOGY</u>									
Constants (aka Parameters)									
Land Degradation Rate (ha/Gl)	<u>da</u>	0.00%		<u>0.30</u>	0.30	0.30	...	0.30	0.30
Evapotranspiration Losses (%)	<u>et</u>	0.00%		50.0%	50.0%	50.0%	...	50.3%	52.6%
Rtu to Hip Conversion (Gl/mm)	<u>yhi</u>	0.00%		<u>1.01</u>	1.01	1.01	...	1.01	1.01
Rainfall to Water Conversion (Gl/mm)	<u>yhr</u>	0.00%		<u>0.8263736</u>	0.8263736	0.8263736	...	0.8263736	0.8263736
Policy Levers									
RBC Irrigation Allocation (%)	Aloc	0.00%		<u>100.0%</u>	<u>100.0%</u>	<u>100.0%</u>	...	<u>99.7%</u>	<u>97.4%</u>
Land Resources									
Land Endowment (ha)	AE	0.00%		<u>195,000</u>	195,000	195,000	...	195,000	195,000
Useable Land Endowment (ha)	AU	0.11%		195,000	194,811	194,621	...	175,519	175,317
Area Planted (ha)	A	0.60%		102,048	104,221	106,164	...	175,519	175,317
Land Utilisation	a	0.71%		0.52	0.53	0.55	...	1.00	1.00
Water Resources									
Drought Severity Index Anomaly	dsia	na		<u>-9.59%</u>	<u>-9.59%</u>	<u>-13.38%</u>	...	<u>2.87%</u>	<u>25.60%</u>
Actual Rainfall (mm)	Ra	0.07%		<u>485</u>	<u>519</u>	<u>512</u>	...	<u>452</u>	<u>415</u>
Trend Rainfall (mm)	Rt	0.06%		<u>455</u>	<u>455</u>	<u>455</u>	...	<u>483</u>	<u>483</u>
Useable Actual Rainfall (mm)	Rau	0.06%		182	194	192	...	171	164
Useable Trend Rainfall (mm)	Rtu	0.06%		171	171	171	...	182	191
Potential Irrigation Water (Gl)	Hip	0.06%	172	172	172	172	...	184	192
Regulated Irrigation Water (Gl)	Hir	0.06%	172	172	172	172	...	184	188
Trend Rainfall Water (Gl)	Hrt	0.06%	141	141	141	141	...	151	157
Actual Rainfall Water (Gl)	Hra	0.06%	141	150	161	159	...	141	135
<u>RIVER BASIN MACROECONOMY</u>									
Constants (aka Parameters)									
Worker Saving Ratio	<u>ow</u>	0.00%		0.02	0.02	0.02	...	0.02	0.02
Farmer Saving Ratio	<u>ofr</u>	0.00%		0.27	0.27	0.27	...	0.27	0.27
Financial Capital Turnover (times pa)	<u>k</u>	0.00%		2	2	2	...	2	2
Employment-Wage Coefficient	<u>e</u>	0.00%		0.1	0.1	0.1	...	0.1	0.1

Inflation-Wage Coefficient	ρ	0.00%	0.9	0.9	0.9	...	0.9	0.9
Productivity-Wage Coefficient	γ	0.00%	0.9	0.9	0.9	...	0.9	0.9
Policy Levers								
RBC Irrigation Water Price (\$/Ml)	Ph	0.68%	<u>\$30</u>	<u>\$30</u>	<u>\$30</u>	...	<u>\$62</u>	<u>\$83</u>
RBC Carbon Emissions Price (\$/t)	Pg	na	<u>\$0</u>	<u>\$0</u>	<u>\$0</u>	...	<u>\$0</u>	<u>\$0</u>
Price Indices								
Rice Export Price Index	prx	0.60%	<u>1.000</u>	1.006	1.012	...	1.808	1.819
Rice Export Inflation Rate (% pa)	gprx	0.00%	<u>0.60%</u>	0.60%	0.60%	...	0.60%	0.60%
Wheat Export Price Index	pwx	0.50%	<u>1.000</u>	1.005	1.010	...	1.638	1.647
Wheat Export Inflation Rate (% pa)	gpwx	0.00%	<u>0.50%</u>	0.50%	0.50%	...	0.50%	0.50%
Domestic Price Index	p	0.70%	<u>1.000</u>	1.007	1.014	...	1.995	2.009
Domestic Inflation Rate (% pa)	gp	0.00%	<u>0.70%</u>	0.70%	0.70%	...	0.70%	0.70%
Labour Resources								
Workforce (workers)	N	0.30%	42,281	42,408	42,535	...	56,877	57,048
Workforce Growth (% pa)	gN	0.00%	<u>0.3%</u>	0.3%	0.3%	...	0.3%	0.3%
Employment (workers)	L	0.22%	42,281	42,434	43,014	...	58,566	58,169
Labour Utilisation	e	0.08%	1.000	1.001	1.011	...	1.030	1.020
Unemployment Rate (%)	u	na	0.0%	-0.1%	-1.1%	...	-3.0%	-2.0%
Money Wage Rate (\$/worker pa)	w	0.82%	<u>\$1,510</u>	\$1,526	\$1,545	...	\$3,411	\$3,455
Real Wage Rate (\$/worker pa)	wr	0.12%	<u>\$1,510</u>	\$1,516	\$1,523	...	\$1,710	\$1,720
Real Wage Bill	Wr	0.34%	\$63,844,177	\$64,321,684	\$65,519,441	...	\$100,150,229	\$100,042,132
Wage Bill Share	ws	0.23%	0.854	0.858	0.859	...	0.721	0.729
Money Wage Growth Rate	gw	na	0.0%	1.1%	1.2%	...	1.4%	1.3%
Real Wage Growth Rate	gwr	na	0.0%	0.4%	0.5%	...	0.7%	0.6%
Real GDP per Workforce Member	Yr/N	0.27%	\$1,768	\$1,768	\$1,793	...	\$2,443	\$2,404
Real Labour Productivity	Yr/L	0.35%	\$1,768	\$1,767	\$1,773	...	\$2,373	\$2,358
Capital Resources								
Capital Stock	K	2.06%	\$46,493,051	\$49,012,013	\$51,795,942	...	\$434,015,362	\$438,555,817
Real Capital Stock	Kr	1.35%	\$46,493,051	\$48,671,314	\$51,078,342	...	\$217,564,241	\$218,312,107
Capital-Output Ratio	v	0.77%	0.622	0.649	0.670	...	1.566	1.592
Capital-Labour Ratio (\$/worker)	x	1.12%	\$1,100	\$1,147	\$1,187	...	\$3,715	\$3,753
Profit Rate (% pa)	r	na	12.4%	11.4%	10.9%	...	15.1%	13.5%
Real Profit Rate	rr	na	11.7%	10.7%	10.2%	...	14.4%	12.8%
Average Debt	D	1.01%	\$42,778,683	\$42,878,529	\$44,028,494	...	\$125,599,167	\$128,816,635
Average Equity	E	3.15%	\$3,714,368	\$6,133,484	\$7,767,448	...	\$308,416,196	\$309,739,182
Debt:Equity Ratio	d	2.07%	11.517	6.991	5.668	...	0.407	0.416
Interest Rate (% pa)	i	0.35%	<u>3.7%</u>	<u>3.7%</u>	<u>3.7%</u>	...	<u>5.2%</u>	<u>5.2%</u>
Real Interest Rate	ir	0.42%	3.0%	3.0%	3.0%	...	4.5%	4.5%
Gross Operating Surplus	R	na	\$5,744,108	\$5,595,980	\$5,638,153	...	\$65,738,268	\$59,202,241
Real Gross Operating Surplus	Rr	na	\$5,744,108	\$5,557,081	\$5,560,040	...	\$32,953,434	\$29,470,743
Gross Operating Surplus Share	rs	na	0.077	0.074	0.073	...	0.237	0.215
GOS less Interest Bill	Rn	na	\$4,161,297	\$4,003,922	\$3,997,675	...	\$59,170,637	\$52,442,791
Real GOS less Interest Bill	Rnr	na	\$4,161,297	\$3,976,089	\$3,942,290	...	\$29,661,196	\$26,105,904
Consumption Expenditure								
Consumption	C	1.21%	\$72,337,492	\$73,119,254	\$75,523,804	...	\$259,898,811	\$260,101,821
Real Consumption	Cr	0.51%	\$72,337,492	\$72,610,977	\$74,477,470	...	\$130,282,687	\$129,478,106
Consumption Ratio	c	0.06%	0.968	0.969	0.977	...	0.938	0.944
Investment and Saving								
Investment	I	na	\$942,136	\$2,518,962	\$2,783,929	...	\$226,232	\$4,540,455
Real Investment	Ir	na	\$942,136	\$2,501,452	\$2,745,359	...	\$113,406	\$2,260,228
Saving by Workers	Sw	0.94%	\$1,276,884	\$1,295,439	\$714,189	...	\$1,336,646	\$1,261,212
Saving by Farmers	Sr	na	\$1,123,550	\$1,081,059	\$1,079,372	...	\$15,976,072	\$14,159,553
Saving	S	na	\$2,400,434	\$2,376,498	\$1,793,561	...	\$17,312,718	\$15,420,765
Real Saving	Sr	na	\$2,400,434	\$2,359,978	\$1,768,713	...	\$8,678,560	\$7,676,423
Saving Ratio	s	na	0.032	0.031	0.023	...	0.062	0.056
Government Accounts								
RBC Receipts	Tx	0.74%	\$5,149,641	\$5,127,835	\$5,239,289	...	\$11,685,200	\$15,350,920
RBC Real Receipts	Tr	0.04%	\$5,149,641	\$5,092,189	\$5,166,702	...	\$5,857,584	\$7,641,653
RBC Expenditure	Gx	0.74%	\$5,149,641	\$5,127,835	\$5,239,289	...	\$11,685,200	\$15,350,920
RBC Real Expenditure	Gr	0.04%	\$5,149,641	\$5,092,189	\$5,166,702	...	\$5,857,584	\$7,641,653
RBC Surplus/Deficit	Bgt	na	\$0	\$0	\$0	...	\$0	\$0
RBC Receipts Share	ts	0.52%	0.069	0.068	0.068	...	0.042	0.056
Trade with RoA/RoW								
Exports	X	1.28%	\$89,816,336	\$90,601,428	\$92,866,194	...	\$328,917,684	\$327,638,760
Real Exports	Xr	0.57%	\$89,816,336	\$89,971,626	\$91,579,593	...	\$164,880,630	\$163,097,843
Imports	M	1.23%	\$88,358,038	\$90,743,892	\$93,856,562	...	\$311,831,198	\$316,758,450
Real Imports	Mr	0.52%	\$88,358,038	\$90,113,100	\$92,556,240	...	\$156,315,476	\$157,681,649
Balance of Trade	Bxm	na	\$1,458,298	-\$142,464	-\$990,368	...	\$17,086,486	\$10,880,310
Gross Domestic Product								
GDP1=Sales-Inputs	Y	1.27%	\$74,737,926	\$75,495,751	\$77,317,365	...	\$277,211,529	\$275,522,587
GDP2=W+R+T	Y	1.27%	\$74,737,926	\$75,495,751	\$77,317,365	...	\$277,211,529	\$275,522,587
GDP3=C+I+(G-T)+(X-M)	Y	1.27%	\$74,737,926	\$75,495,751	\$77,317,365	...	\$277,211,529	\$275,522,587
Real Gross Domestic Product	Yr	0.57%	\$74,737,926	\$74,970,955	\$76,246,183	...	\$138,961,247	\$137,154,529

Appendix B – Key Equations of the River Basin Model

Some key relationships in the computer simulation model of the River Basin Economy are set out below. Note that ‘pa’ refers throughout to ‘per annum’. All rice and wheat produced is exported, with virtually all inputs to production and commodities consumed being imported. The structural form of the model is a system of 170 equations and identities, comprising 46 for the rice sub-model, 46 for the wheat sub-model, 14 for the ecology section, and 64 for the macroeconomic section.

With the help of just 26 Greek letter constants (aka parameters) these relationships, together with exogenous export and domestic prices, mutually determine all quantities and dollar values, plus the realised rates of profit on capital (rr_t % pa for rice and rw_t % pa for wheat).

Farmers have *static expectations*, i.e. they expect to realise rr_{t-1} % pa on capital devoted to rice and rw_{t-1} % pa on capital devoted to wheat. One or both sets of farmers may not realise their expectations at harvest/sale time in any given year, of course, and this is what primarily drives the economy’s dynamics.

The river basin’s endowment of arable land, suitable for raising either crop, is fixed at AE_t hectares. Potential irrigation water (Hlp_t gegalitres pa for rice) and normal rainfall water (Hrn_t gegalitres pa for wheat) depend upon the basin’s fluctuating annual rainfall totals (in millimetres), after a fixed percentage of evapotranspiration losses has been subtracted.

Investment in Area Planted (hectares pa)

$$Ar_t = Ar_{t-1} (1 + \varphi [rr_{t-1} - nr_t]) \text{ for rice; and}$$

$$Aw_t = Aw_{t-1} (1 + \varphi [rw_{t-1} - nw_t]) \text{ for wheat.}$$

If $Ar_t + Aw_t > AE_t$ the crop with the bigger expectation of profitability (i.e. the two r_{t-1} % pa realised profit rates) gets all the area it wants and the balance goes to the other crop. The two n_t % pa normal profit rates comprise the common interest rate plus a crop-specific risk premium. The term inside square brackets is the ‘profitability gap’ between the farmers’ expected return on capital and opportunity cost of capital. As this gap widens and narrows, so the river basin economy dynamically expands and contracts.

Investment in Land&Water (dollars pa)

$$Ir_t = Ir_{t-1} (1 + \varphi [rr_{t-1} - nr_t]) \text{ for rice.}$$

Investment in Land (dollars pa)

$$Iw_t = Iw_{t-1} (1 + \varphi [rw_{t-1} - nw_t]) \text{ for wheat.}$$

Wage Rate (dollars/worker pa)

$$w_t = w_{t-1} (1 + s[s_t - 1] + \rho gP_{t-1} + \gamma gq_t) \text{ and } w_t \geq w_{t-1} \text{ with } s_t = L_t/N_t$$

being the labour utilisation ratio, gP_{t-1} last year’s domestic inflation rate, and gq_t the growth rate of labour productivity. The inequality ensures that, unlike real wage rates, average money wage rates never fall (as in real-world advanced economies).

Crop Produced (tonnes pa)

$Q_t = A_{t-1}b_t$ for both crops, where crop yield (tonnes/hectare) is

$b_t = b_{t-1}(1 + \beta g b_{t-1})$ without water constraints, but otherwise is reduced by the fractions $Htr_t/H'p_t$ for rice and Hra_t/Hrn_t for wheat, where the numerators are irrigation water released and actual rainfall water, respectively. The variable $g b_{t-1}$ is last year's growth rate of crop yield, which rises at the same rate as real crop yield investments (in constant dollars pa). These yield-raising investments comprise land improvements by the farmers themselves, plus government expenditures on research and agricultural extension by the River Basin Commission (RBC).

Realised Profit (dollars pa)

On each crop, this is Sales Revenue [Q_t times export price] minus the Variable Cost of wages, seed, fertiliser, fixed asset rentals, and RBC water and carbon charges.

Employment (workers pa)

$L_t = Q_t/a_t$ for both crops, where labour productivity (a_t tonnes/worker) grows at the fixed rate ($g a_t$ % pa). The economy's workforce (N_t workers pa) also grows at a fixed rate ($g N_t$ % pa).

Note: Excel spreadsheets for the River Basin Model are available from the corresponding author. The five model runs available are: Unconstrained, Land Constrained, Rain Water Constrained, Irrigation Water Constrained, and Fully Constrained