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Water allocation using system dynamic modelling in the aquaculture integrated with small-scale irrigation systems in Malawi

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ABSTRACT

The agricultural sector is faced with numerous challenges including climate change and water scarcity in many developing countries. In order to address scarcity and improve water use efficiency for rural farmers, fish farming is being integrated with small-scale irrigation. However, there are challenges in how to allocate water between the two farming enterprises. This study explored the capabilities of system dynamics to allocate water between a fish pond and a crop field in Chingale, Malawi using a system dynamic software, Vensim™ PLE. For soil water and pond water, a simple water balance structure was built and connected to the crop growth structure. Simulations run for 125 days corresponding to the maize growth period. Model results are similar to the actual yield (about 3.5 ton/ha for hybrid) and biomass production (about 7 ton/ha) in the area. Results also show it was possible to maintain pond water depth at recommended depths for raising fish: fish stocking (1 m), operation of the pond (1.5–2.0 m) and harvesting of the fish (less than 1.2 m) throughout the maize growing period. While the study did not comprehensively build and simulate fish growth, the use of such simple tools would benefit rural farmers with few resources. Based on the promising capabilities and the results of the tool it is recommended that further comprehensive analysis to fully incorporate all key sub-components affecting crop and fish growth be carried out.

1.0. Introduction

In sub-Saharan Africa (SSA) countries, the agriculture sector continues to dominate its economies by providing income and livelihoods to its citizens (Mango et al., 2018). According to the latest Malawi annual economic report agriculture, forestry and fishing sector contributed to around 22.8% of the total overall gross domestic product (GDP) in 2020 and is projected to increase to 23.4% in 2022 (Government of Malawi, 2021). The agriculture sector employs more than 85% of the rural population which makes up more than 80% of the total population (Government of Malawi, 2018). The sector is, however, affected by various challenges that are crippling its productivity including natural resources degradation, unreliable rainfall due to climate variability and climate change, as well a lack of service support and poor infrastructure (Phiri et al., 2012; Nhamo et al., 2016; Lindsjö et al., 2021). Another critical challenge affecting agriculture production in Malawi is the small size of land available to most rural farmers (Mungai et al., 2020). Muyanga et al. (2020) estimated that the majority (76%) of smallholder farmers own on average less than 1.0 ha of land. However, smallholder farmers contribute over 90% of the total agricultural production (Government of Malawi, 2007).

As the population continue to grow, demand for food increases which will require sustained agricultural production. There is a critical need to find means of improving production. This can either be through addressing the means of production, such as the size of landholding or by improving resource use efficiency. With advances in technology and research, it is possible to improve resource use efficiency and increase agricultural production in areas of water use (irrigation), fertilisers, crop variety and animal species.

Irrigated agriculture is one of the solutions to increasing agricultural production amidst unreliable rainfall in Malawi (Chafuwa, 2017). While in the past, it has been easily adopted by large scale or commercial

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farming, and evidence shows increasing small-scale rural farmers are adopting the technology. In some parts of Malawi such as Chingale, rural farmers have adopted small-scale irrigation farming as a resilience tool towards climate variability and climate change impacts (Mango et al., 2018). Irrigation farming in Chingale was found to improve household food security through an increase in both crop production and income levels for farmers (Kalima, 2008; Mango et al., 2018). However, with poor water resources infrastructure available to farmers in rural areas, aquaculture integrated with irrigation seems to become an evermore viable option and is also being increasingly practiced in many areas in Malawi (Dey et al., 2010; Kam et al., 2013). In addition to keeping fish which is also important for agricultural diversification (Djurfeldt et al., 2018), ponds also serve as a water reservoir. Farmers raise fish in ponds and use the same water from the pond to irrigate small crop fields.

Whilst aquaculture integrated with irrigation offers hope for many poor farmers against shocks from climate variability and climate change, simple decision support tools are required to help farmers make appropriate water resource planning decisions in order to maximize output with limited resources. Several tools have been developed for water resources planning (Giupponi and Sgobbi, 2013). However, these tools have mostly served the development of water resources and are often too complex and applied at a large catchment scale requiring a huge amount of data. This has tended to leave out the multiple and conflicting water use (Cai et al., 2014; Rinaldi and He, 2014). System dynamic models are one of the groups of tools being used in studying multiple water use and planning. For instance, Phiri and Mulungu (2019) used simulation to integrate water use and development among hydropower, irrigation, and water supply in Nkhata-bay district in Malawi. In their scenario simulation, they were able to isolate the most possible option for development given the available water resources. Similarly, Kotir et al. (2016) developed a system dynamic model to examine the long-term changing behaviour of the Volta River Basin in West Africa by considering components of population, water resources, and agricultural production. System dynamic models' popularity lies in their ability to model complex natural systems whose behaviour are non-linear (Garcia, 2020). Advances in system dynamics development hinges on the motivation that an 'event-oriented view of the world or linear thinking' cannot fully address complex, real-world challenges that are mostly non-linear (Abadi et al., 2015). System dynamics is a theory of system structure and a set of tools for representing complex systems and analysing their dynamic behaviour (Forrester, 1971). This approach enables the understanding of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system. The system dynamic model differs from other approaches, as it is able to study complex systems using feedback loops, stocks and flows (Garcia, 2020). In any modelling effort, it is important to remember that not understanding patterns of behaviour is much more important than obtaining an exact prediction of a variable value at every single point in time (Forrester, 1961).

With cutting edge research in computer technology, system dynamics software models have been developed and applied in many diverse systems. It has found application in a wide range of areas, for instance, population, environment, economics, and agricultural systems, which generally interact strongly with each other. In agriculture, system dynamics has been used at various levels and sizes. Models exist for particular crops, water management and even agriculture development in general. Due to the complex nature of the problems that need to be addressed in water management, the use of dynamic simulation models has been a long-standing tradition (Rogers and Fiering, 1986; Winz and Brierly, 2007). Further, Abadi et al. (2015) outlined several past usages of system dynamic modelling including sustainability analysis, flood routing, water resources carrying capacity, urban water demand, and aquifer studies. One of the detailed works in agriculture using system dynamics approach software has been carried out by Hartmut Bossel in his system zoo collections. Bossel (2007) using the Vensim™ Personal Learning Edition (PLE) has modelled several agriculture-related systems including watershed management, field crop production, fish dynamics, fish ponds and soil water dynamics.

Considering the diverse challenges facing localities, simple context-based tools can be easily used at a farm level by rural farmers who are not only poor but have a low level of education. This study, therefore, was conducted to explore the use of a system dynamic model (SDM) to develop a simple water allocation decision support tool for small scale farming in rural Malawi. In this study, Vensim™ PLE was used to model water allocation between a fish pond and a maize field. The uniqueness of the study lies in its simplification and reducing variables to allow farmers to only use pond water depth as a water allocation rule.

2.0. Materials and methods

2.1. Study area

The study was conducted in Chingale, Traditional Authority (TA) Mlumbe, west of Zomba District, Malawi (Fig. 1). According to the 2018 census, the population of TA Mlumbe was 127,300 (Government of Malawi, 2019). Chingale is generally isolated from the main trading centres and commercial towns of the district because of poor road infrastructure and inaccessibility because of the Zomba Mountain in the east (Kalima, 2008) and the Shire River to the west. The main livelihood in the area is semi-subsistence agriculture with landholding of about 1.3 ha (ha) per household, of which 24 percent is irrigated (Kam et al., 2013; Cai et al., 2014). Major crops grown include maize, sweet potato, vegetables, cassava, and peanuts. In addition to crop production, Cai et al. (2014) identified 741 fish ponds with an average surface area of 223 m^2 where farmers practice fish farming.

A farmer's fish pond and a maize plot (Fig. 2) in a community fish farming club in Chingale were purposively selected where the modelling study was done. Fish is raised in a pond which also supplies water to the maize plot. In return, the maize stovers, after harvest is put in the pond as a source of nutrients for the fish. Further, when the pond is emptied of water, the pond mud or effluent may also be used as fertiliser in the maize field and may reduce the amount of chemical fertilizer required to apply in the field In Chingale, with the help of non-governmental

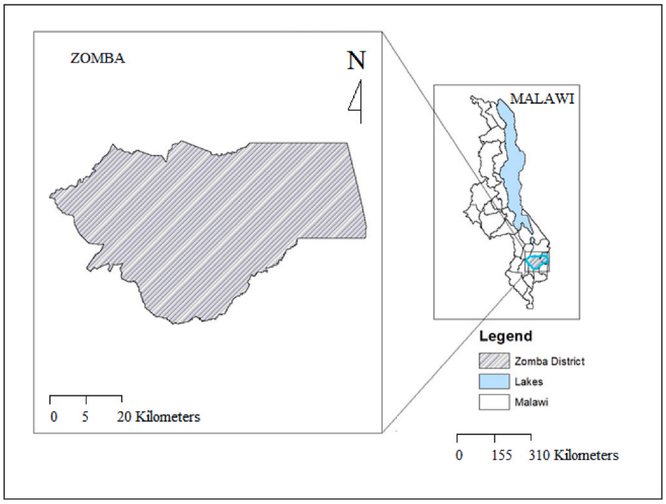

Fig. 1. Study area – Chingale, Zomba district, Southern Malawi.

Fig. 2. Fish pond and maize plot used for water allocation modelling in Chingale, Zomba, Malawi.

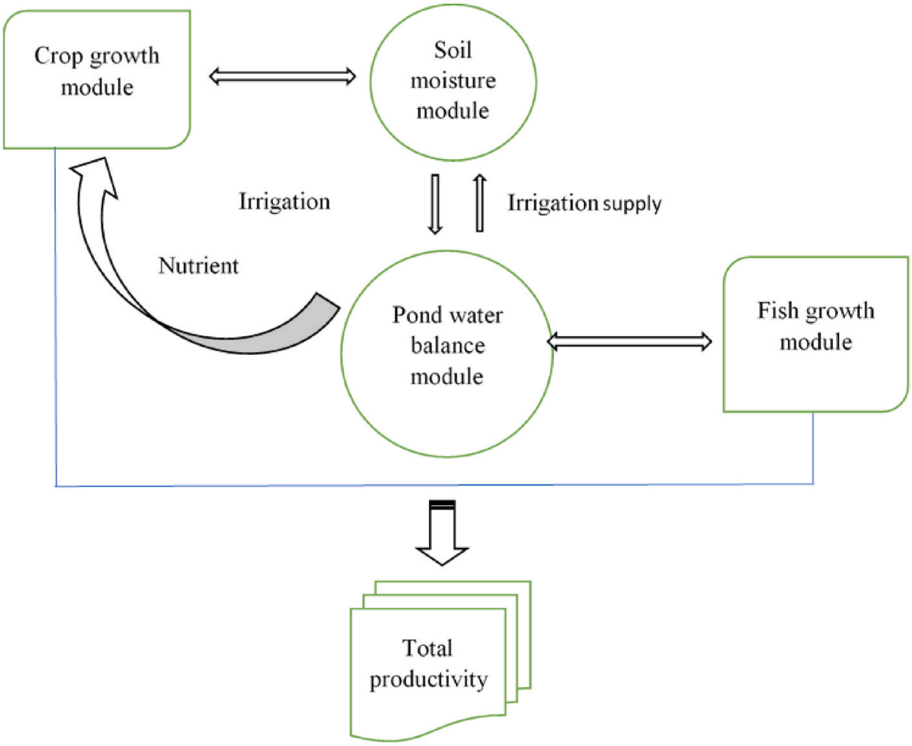

Fig. 3. Schematic model framework and its interactions.

organisations and research institutions such as WorldFish and International Water Management Institute (IWMI), farmers develop and manage water resources for irrigation by constructing simple infrastructure such as canals to divert water from nearby streams or rivers to fish ponds and irrigation plots.

The mean annual rainfall in Zomba ranges from 902 mm to 1317 mm (Government of Malawi, 2021). Though Zomba receives this amount of rainfall annually, it is almost entirely concentrated in the wet season. It has also been observed that the rainfall is unevenly distributed coupled with droughts and floods throughout the country due to climate change variability (Ngongondo, 2006; Ngongondo et al., 2011; Haghtalab et al., 2019).

2.2. Model building and simulations

2.2.1. Data requirements

The study used the following annual climatic data: rainfall, maximum and minimum temperature, relative humidity, sunlight or sunshine hours, wind speed, and evaporation. The data was sought from the Department of Climate Change and Meteorological Services in the Ministry of Forestry and Natural Resources, Chancellor College and Chingale Meteorological stations. Minimum temperature, maximum temperature and relative humidity, Reference Evapotranspiration was calculated using the recommended AquaCrop ETo Calculator software (Raes et al., 2009, 2018). For simulations, the period corresponded to the growth days of the maize (125 days).

2.2.2. Vensim model description

Vensim™ PLE is one of the software in the system dynamic (SD) model group. Vensim™ PLE is an interactive software environment that allows the development, exploration, analysis and optimization of simulation models (Garcia, 2018). It is developed by Ventana Systems Inc.

Vensim™ PLE was chosen due to its ability to combine complex systems or components of natural systems. It can simulate the dynamic behaviour of systems, that are impossible to analyse without appropriate simulation software because the behaviour of such systems is unpredictable due to many influences and feedback. Vensim™ PLE helps with causality loops identification and finding leverage points. In this study, it is used to model the water allocation by simulating fish and crop growth.

Two sub models were considered to successfully model the water allocation in the aquaculture integrated with irrigation: crop and fish growth models. Fig. 3 shows how the sub-models/systems interact in integrated aquaculture and small-scale irrigation farming. In the schematic model, water is considered the most limiting factor as such systems depend on the water inflow from a stream. As water is supplied into the pond, it inhabits the fish while at the same time water is taken from

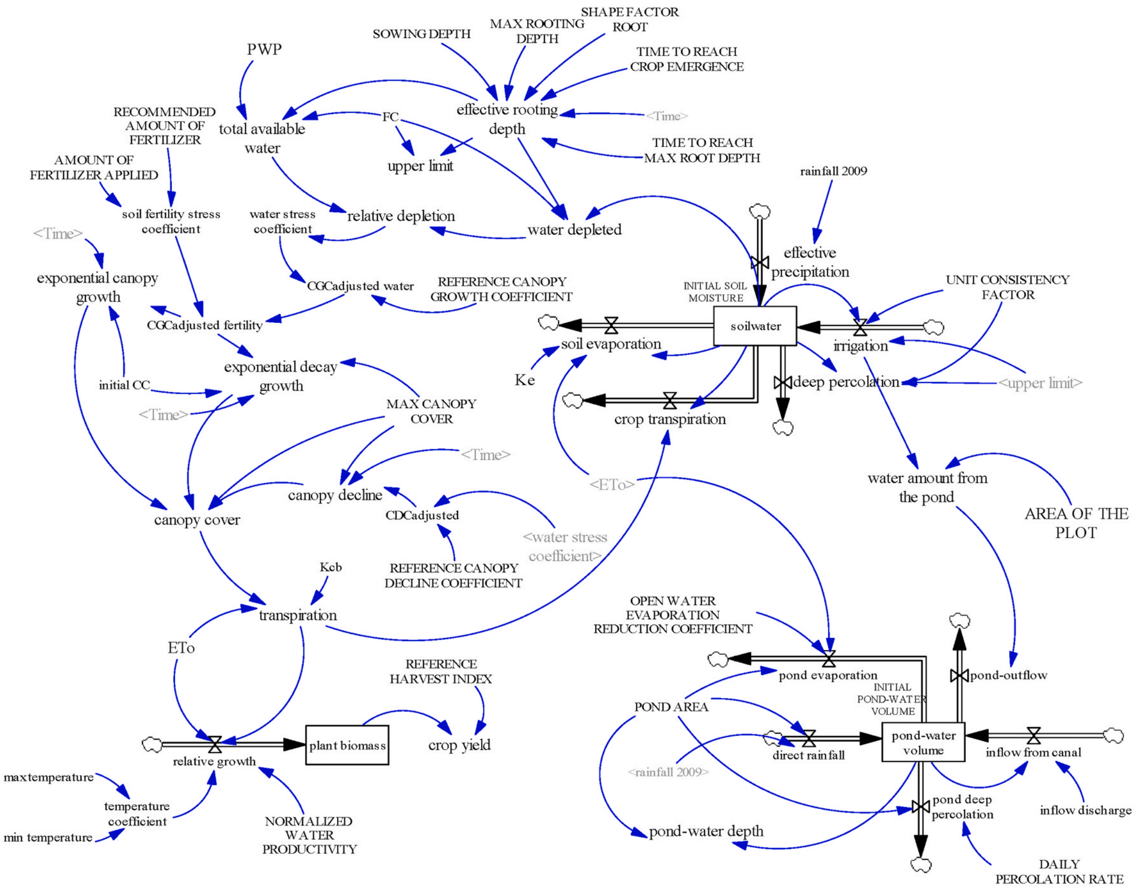

Fig. 4. Structure of the water allocation model in Vensim environment.

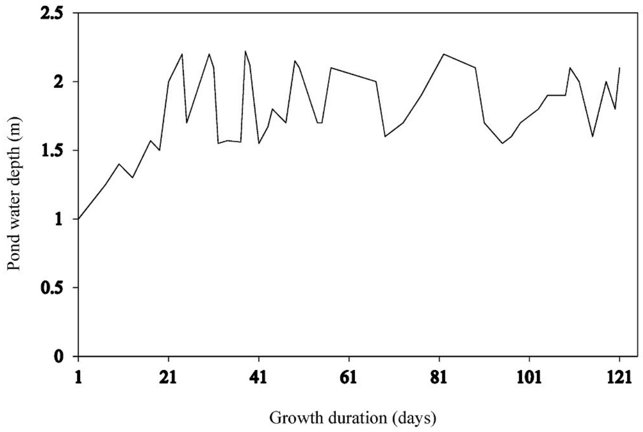

Fig. 5. Pond water depth development throughout the maize growth period.

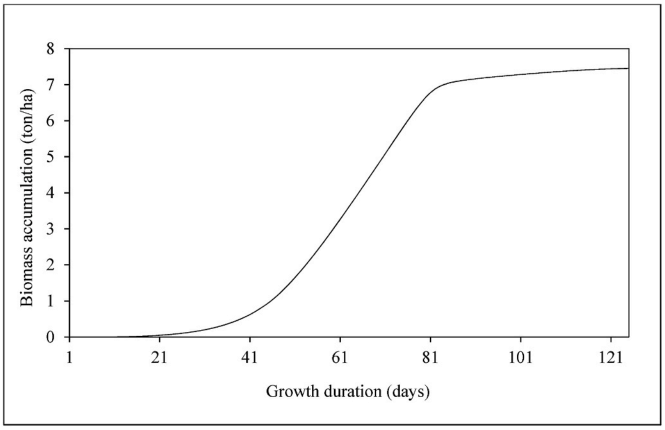

Fig. 6. Plant biomass development throughout the growth period.

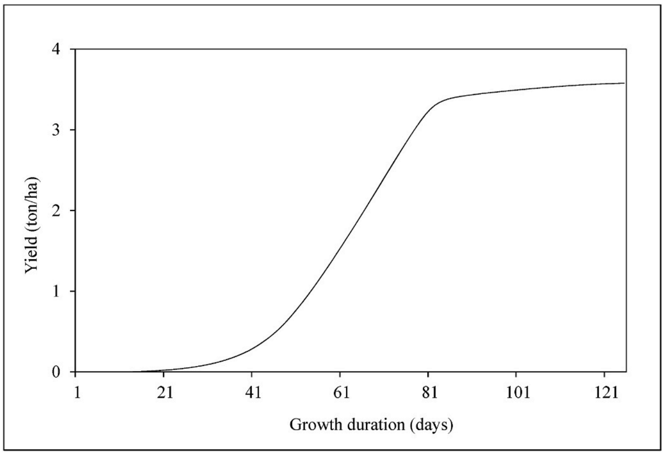

Fig. 7. Crop yield simulation.

the pond to supply the crop field. The water uptake in the soil profile depends on the crop water requirement which is a function of the prevailing evapotranspiration (ET), and the soil moisture conditions. With enough water in the soil, the crop growth will be normal but with soil water shortages the crop growth will be retarded in its canopy development, flowering, and yield formation depending on which stage of development is the stress.

2.2.3. *Crop growth model*

Deciding on the overall water demand of the crop or fish could be difficult if not looking at how the crop develops and consumes water, and how fish grow favourably in a certain volume of water as it is related to the depth and particular species. In this regard, crop and fish growth models are sought so that their water requirements are tracked from the germination to harvest period and from fingerling for fish to maturity.

Among the many crop growth models available, FAO's AquaCrop has been selected to model crop growth by simulating the crop yield response to water. How the AquaCrop is used, and its applicability is well documented by Raes et al. (2009). AquaCrop has also been validated and applied in different countries globally and for different crops. In this regard, AquaCrop was set and run for Malawi and its results were compared to the typical yields being harvested. The underlying equations in the build-up of the AquaCrop, the parameters/output for the runs of the AquaCrop in Malawi are used or exported into the structure of the Vensim™ PLE to model the crop growth.

3.0. Results and discussion

3.1. *Model structure development*

Following the decision on key sub models/systems that interact in integrated aquaculture and small-scale irrigation farming, a generic Vensim™ PLE model was built. The structure was built so that the equations could easily be solved and simulated successfully by Vensim™ PLE. This study developed water balance equations (subtracting the outflows from inflows) in both the soil and the pond. Fig. 4 illustrates the developed model structure. As shown in Fig. 4, the convention used in the Vensim™ PLE is that all constants are in capital letters and all other variables, stock/level parameters are in small letters. For instance, below, the initial pond water volume is a constant and is written in capitals in the Vensim™ PLE program. The inflow discharge is a variable and is written in small letters. The state variables are written in the square boxes while variables influencing the state variables which are called the 'rate variables' are below the valve sign in the influencing arrow. Arrows show the direction of influence; thus an arrow originates from the influencing variable or constant to the variable which is being influenced. A description of all parameters and equations used in the model is presented in the Appendix.

3.2. *Model description*

Fig. 4 illustrates the critical model components. To successfully allocate water between the fish pond and the maize field it is ideal to connect these components and look at their processes and characteristics simultaneously – how they influence each other dynamically. In this study, the only elements deemed important in the system are considered and described. The starting point is taken as the pond since the pond acts as a water reservoir for crop production apart from the rearing of fish in it. The sources of water in the pond are rainfall and the inflows from the canal, which is a diversion from the nearby stream in the project area. The pond water volume is calculated from a pond water balance (+ direct rainfall + inflow from canal - pond deep percolation - pond evaporation - pond outflow) and consideration of the initial pond water volume. When the pond water volume is assessed, the temporal depth of the pond is calculated with the pond area. However, the model assumed that the inflow into the pond from the streams or rivers remained constant or had no disturbances in terms of the volume diverted over the growing season.

The pond water depth is compared to the three operation depths of the pond for which the raising of fish in a pond is suitable (Kam and Hoanh, 2007). In this case, fish production is only a function of water availability holding all other factors such as temperature and fish feed constant. This assumption was necessary because it was difficult to get quantitative data on the nutrients and feeding of the fish in the pond at the time of the study. However, such data would be useful for comparison if the model is extended to the actual production of fish where several factors are allowed to vary. As the model is simulated based on these determinant depths, a period called Pond Water Availability Period (PWAP) is then deduced. This is the period where the raising of fish is possible considering only water as the limiting factor.

Apart from rainfall, the pond outflow is the main source of water (soil moisture) for crops. The two sub-models are thus connected through the outflow (determined in the model through “water from the pond”), which gets into the soil water balance as irrigation. The outflow/water from the pond is determined by the model based on the soil moisture conditions and also on evapotranspiration. The soil water balance (+ irrigation + rainfall – percolation – evaporation - transpiration) with initial soil water calculates the amount of soil water that is available for plant consumption. However, the amount of water available to the plant is influenced by the root depth of the plant at a particular developmental stage of the crop. In the early stage of crop growth, the roots are not deep and completely developed, hence the crop can only extract water in the shallow soil profile. As the crop develops the soil profile from which to extract water increases until the final maximum of the root depth. Effective rooting depth has been added to the model to simulate the temporal depth of the crop and hence get the exact amount of water required for the crop.

Soil water stress affects the development of the canopy cover, the expansion of the root zone, and results in stomata closure. It also reduces crop transpiration rate, alters the Harvest Index, and triggers early canopy senescence (Raes et al., 2012; Nemeskéri and Helyes, 2019; Parkash and Singh, 2020). Soil water stress affects the above processes when the stored soil water in the root zone drops below a threshold level. In this model, the soil water stress coefficient links the soil water balance to crop growth. AquaCrop’s soil water stress coefficient adjusts the Reference Canopy Growth Coefficient (CGC). After being adjusted with the soil water stress coefficient the Growth Coefficient is then adjusted further by the soil fertility stress coefficient. The soil fertility stress coefficient is the expression of the nutrient status of the soil. In the study area, the nutrients are either supplied through chemical fertilizer or organic manure. In Malawi, there exist area-specific fertilizer recommendations for hybrid maize grown by smallholder farmers. In Chingale, Zomba, for instance, the requirements are 69: 21: 0 + 4 S corresponding to kilograms of nitrogen: phosphate: potassium + sulphur (S) applied per hectare in the fertilizer (Benson, 1999). The soil fertility stress is thus calculated based on how much fertilizer has been applied by the farmer compared to the recommended figures of the area.

The canopy growth coefficient adjusted for soil fertility stress and soil water stress is used in the calculation of the canopy cover development. In absence of stress, the canopy cover development will not be affected, and the growth will be normal. In case there is stress in either fertility or available water then canopy cover development will be affected. The overall result is a reduction in the final crop yield. Canopy cover influences crop transpiration. A larger canopy cover means that there is a wider area from which the crop can transpire and hence there is increased transpiration. It is the same transpiration rate that affects the uptake of soil water in the combination process of Evapotranspiration thereby forming another connection between crop growth and soil water. The aboveground biomass is derived from the simulated amount of water transpired considering the crop water productivity. The crop water productivity expresses the aboveground dry matter (g or kg) produced per unit of land area (m^2 or ha) per unit of water transpired (mm). A wide range of experiments have shown that the relationship between biomass produced and water consumed by a given species is highly linear (Steduto et al., 2007). In this model, crop water productivity is taken as 33.7 (g/m^2) after Raes et al. (2009). The temperature coefficient has been calculated by considering the threshold air temperatures (base temperature and upper temperature; 8 °C and 30 °C respectively). Outside the temperature range, crop growth is considered to be impossible because it is either too cold or hot. Yield is calculated from the aboveground biomass through the harvest index. The harvest index for maize ranges from 48 to 52% (Raes et al., 2009).

3.3. Simulations results

The structure and equations of the model, which were developed and explained under the model description and others included in the appendix were simulated successfully. The inflow data was based on the daily recorded data at the pond. Figs. 5–7 present graphs for selected parameters that are key for water allocation. These main parameters include pond water depth, biomass, and crop yield. Other parameters that were simulated include: pond water volume, irrigation requirement, pond water outflow, and soil water but these have not been presented in this paper.

Fig. 5 shows pond water depth developments in the pond when the pond is operational for both crop growth and fish production. The simulation runs from day 1 [April 1] until day 125 [August 3]. This period was chosen as it corresponds to the growing season of maize under irrigation. Often, the crop is planted in late March or early April depending on the prevailing conditions in an area and also how prepared the farmer is. The simulation shows there is an increase in the pond depth from day 1 when the inflows start. The reductions in the depth during the growing period show the outflow from the pond is mainly contributed by the irrigation requirement. There is no time in the growing season when the depth is reduced to zero where the pond would be empty as that would cause detrimental effects to the fish.

According to Kam and Hoanh (2007), the pond water levels for fish production can be divided into three phases. Stocking level is the depth where farmers can start stocking fingerlings into the pond which corresponds to when the depth of the pond reaches 1 m. The pond thereafter is maintained at the depth of 1.5–2.0 m throughout the breeding/growing season for the fish and this is referred to as the operational level. The pond level is then expected to fall to 1.2 m so that harvest of fish can be done, and this depth is called the final harvest level. In this simulation, it can be shown that from day 1, fingerlings could be stocked in the pond. The simulation further shows that the production of the fish may not be affected by water shortage as the depth is maintained well above the optimum depths for all phases. Thus the fish has enough water for its growth.

The development of plant biomass illustrated in Fig. 6 shows that biomass develops until the value of around 7 ton/ha at the maturity of the crop. The aboveground biomass production for every day of the crop cycle is obtained from the normalized water productivity, the daily crop transpiration for that day and the daily reference evapotranspiration for that day as can be seen in the structure of the model above and equations in the Appendix. As expected, the biomass increases as the growing season advance. The biomass plant biomass is further adjusted with the temperature effect. In this case, the temperature has been included by considering the base maximum temperature and minimum temperature beyond which biomass production is impossible. The temperatures, though in Malawi, are mostly within the optimum range for crop production as such there is no adverse effect from temperature.

Illustrates the development of the crop yield. Since the yield is a function of biomass and only adjusted through harvest index, it follows the same trend as the plant biomass. As the harvest index ranges from 48% to 52%, it means the final crop yield will be more or less half the plant biomass. In this simulation, the yield at the maturity time of the crop is around 3.5 ton/ha.

3.4. *Comparison of initial results with actual crop production*

The results from this simulation do not only compare well with obtained biomass and yield in the project area but also across Malawi. The crop production in the year 2010 was about 2.5 tons per hectare. In the winter crop of 2011, the yield was approximately 3 tons per hectare. In Malawi, average maize yield is about 1.7 tons per ha compared to the world average of 1.94 tons per ha to 5.80 tons per ha (Nyirenda et al., 2021). In the simulation, it was assumed that irrigation is optimum, and a certain depletion factor has been assumed that irrigation water will be supplied as long as soil moisture drops to that level. This assumption builds on the assumption that there is a continuous water inflow from streams or rivers during the growing season. The pond acting as a water storage structure in rural areas in Malawi directly addresses the challenge of water unavailability which rural farmers face (Wang and Cai, 2015). Apart from the expensiveness of improved seed, climate change, unproductive soils and variations in variety preferences (Lunduka et al., 2012; Nyirenda et al., 2021), water unavailability has been limiting crop production. Integration of fish farming and irrigation, therefore, contributes to the need for crop water productivity as a solution to food insecurity in Malawi (Nhamo et al., 2016).

4. Conclusion and recommendations

This study focused on exploring the capability of system dynamic modelling, and the simple model that was developed using the Vensim software was able to provide a relatively precise and simple decision tool in allocating water between fish and maize field for rural farmers in Malawi. The crop model was developed with some modifications to the AquaCrop equations, therefore to determine the accuracy of these modifications the results were compared to the crop growth model applied to the same test area, where the crop yields from AcuaCrop and the model were similar. The small differences observed were likely due to the modifications of some of the equations or the simplification of some inputs and parameters so that it was more easily applied in VensimTM software. The crop yields attained in both AquaCrop and the model were also compared to the actual yield in the area and were also found to be similar.

The model was built and simulated for crop production with a predefined operating depth of the ponds depending on the recommended pond depth optimum for a particular fish growth period. This study has successfully shown that with simple system dynamic tools it is possible to guide farmers in rural areas on water resource use efficiency in order to maximize agricultural production amidst the adverse impacts of climate change and climate variability. To fully provide guidance on water allocation in aquaculture integrated with small-scale irrigation farming, it is recommended that the fish model be fully developed to include the effects of fish feed on fish growth.

Credit author statement

All authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix

Model parameters and equations

Pond parameters

INITIAL POND WATER VOLUME = 400 [m3]

POND AREA = 408 [m2]

DAILY PERCOLATION RATE = 0.003 [m/day]

Pond dynamics

inflow discharge = (external daily data input) [m3/day]

inflow from the canal = inflow discharge [m3/day]

direct rainfall = rainfall*POND AREA [m3/day]

pond evaporation = ETo*OPEN WATER EVAPORATION REDUCTION COEFFICIENT*POND AREA [m3/day]

pond-outflow = water amount from the pond*AREA OF THE PLOT [m3/day]

pond-water volume = INTEG(direct rainfall+inflow from canal-pond deep percolation-pond evaporation-"pond-outflow", "INITIAL POND-WATER VOLUME" [m3]

pond-water depth = "pond-water volume"/POND AREA [m]

Soil parameters

INITIAL SOIL MOISTURE = 0.22 [m]

FC = 0.22 [m/m]

PWP = 0.1 [m/m]

AREA OF THE PLOT = 2023.43 [m2]

RECOMMENDED AMOUNT OF FERTILIZER = 4 [bags/ha]

AMOUNT OF FERTILIZER APPLIED = 4 [bags/ha]

UNIT CONSISTENCY FACTOR = 1 [1/day]

Soil water dynamics

irrigation = IF THEN ELSE(soilwater<0.7*upper limit,(upper limit-soilwater)*UNIT CONSTISTENCY FACTOR, 0) [m/day]

upper limit = FC*effective rooting depth [m]

deep percolation = IF THEN ELSE (soilwater>upper limit, (soilwater-upper limit)*UNIT CONSISTENCY FACTOR, 0) [m/day]

rainfall = (external daily data input), see Table 3 [m/day]

effective precipitation = rainfall [m/day]

soil evaporation = Ke*ETo [m/day]

crop transpiration = transpiration [m/day]

water depleted = IF THEN ELSE (soilwater>=FC*effective rooting depth, 0, FC*effective rooting depth-soilwater) [m]

total water available = (FC-PWP)*effective rooting depth [m]

relative depletion = IF THEN ELSE (water depleted>=total available water, 1, water depleted/total available water) water depleted/total available water [1]

water stress coefficient = IF THEN ELSE (relative depletion=0, 1, 1-((EXP ((relative depletion*SHAPE FACTOR)-1)/ (EXP (SHAPE FACTOR)-1)))) [1]

water stress coefficient = 1-relative depletion

soil stress coefficient = IF THEN ELSE (AMOUNT OF FERTILIZER APPLIED=RECOMMENDED AMOUNT OF FERTILIZER, 1, AMOUNT OF FERTILIZER APPLIED/RECOMMENDED AMOUNT OF FERTILIZER)

Crop parameters

SOWING DEPTH = 0.3 [m]

MAX: ROOTING DEPTH = 1.0 [m]

SHAPE FACTOR ROOT = 1.3 [1]

TIME TO REACH CROP EMERGENCE = 5 [day] (from the day of planting)

TIME TO REACH MAX ROOT DEPTH = 67 [day] (from the day of planting)

REFERENCE CANOPY GROWTH COEFFCIENT = 0.2 [1]

SHAPE FACTOR (water coefficient) = 2.9 [1]

Initial CC = 0.012 [1]

MAX CANOPY COVER = 0.80 [1]

REFERENCE CANOPY DECLINE COEFFICIENT = 0.128 [1]

NORMALIZED WATER PRODUCTIVITY = 0.337 [ton/ha]

HARVEST INDEX = 0.48 [1/day]

Crop dynamics

CGCadjusted water = water stress coefficient*REFERENCE CANOPY GROWTH COEFFICIENT [1]

CGCadjusted fertility = soil fertility stress coefficient*CGCadjusted water [1]

exponential canopy growth = initial CC*EXP((Time)*CGCadjusted fertility) [1]

exponential decay growth = MAX CANOPY COVER-(0.25*((MAX CANOPY COVER)2/initial CC)*EXP((-1*Time)*CGCadjusted fertility))[1]

canopy decline = MAX CANOPY COVER*(1-0.05*(EXP((CGCadjusted/MAX CANOPY COVER)*senescence time)-1)) senescence time =

canopy cover = IF THEN ELSE (exponential canopy growth<= (MAX CANOPY COVER/2), exponential canopy growth, IF THEN ELSE (exponential canopy growth > (MAX CANOPY COVER/2), exponential decay growth, IF THEN ELSE (exponential decay growth=MAX CANOPY COVER, MAX CANOPY COVER, IF THEN ELSE (Time>94, canopy decline, 0)))) [1]

transpiration = canopy cover*Kcb*ETo [m/day]

Kcb = (external daily data input), see Table 3 [1]

Ke = (external daily data input) see Table 3 [1]

ETo = (external daily data input), see Table 3 [m/day]

maximum temperature = (external daily data input), see Table 3[°C]

minimum temperature = (external daily data input), see Table 3 [°C]

temperature coefficient = IF THEN ELSE (min temperature>=8:AND:max temperature <=30, 1, 0) [1]

relative growth = temperature coefficient*NORMALIZED WATER PRODUCTIVITY*(transpiration/ETo) [ton/ha]

plant biomass = INTEG (relative growth,0) [ton/ha]

crop yield = REFERENCE HARVEST INDEX*plant biomass [ton/ha]

Simulation time parameters

INITIAL TIME = 1 [day]

FINAL TIME = 125 [day]

TIME STEP = 1 [1]

. (*continued*).

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