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ORIGINAL ARTICLE

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Modelling of water regulating agro-ecosystem services in India

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ABSTRACT

Agroecosystem models are recognized as effective and potential tools for understanding the interactions between different agro-ecosystem components for identifying the suitable management measures and sustainable management agro-ecosystem. The study illustrates the use of models in agroecosystems for simulating water-regulating services in India and emphasizes the vital role of the audience in advancing this research. Developed agro-ecosystem simulation models in India are effectively employed for simulating the water-regulating agroecosystem services, including infiltration, potential groundwater recharge, water storage, surface runoff yield, and soil erosion. Applications of developed infiltration models for constant as well as varying depths of ponding are successfully applied for a range of soils. Simulated potential groundwater recharge from WHSs (Water Harvesting Structures) by the developed potential groundwater recharge simulation model varied between 83 and 90% of stored water in the WHSs. Simulation of soil erosion by a derived model ranged from 0.09-3.83 t ha^{-1} yr^{-1} for different crops and cropping systems. Modeled surface runoff by the NAPI-based rainfall-runoff model for an agro-ecosystem's degraded land use system ranged from 10-20% of the rainfall. Simulation studies on a few water-regulating agro-ecosystem services employing the derived models showed varied hydrologic responses of varying land use systems in India's agro-ecosystem. In conclusion, these agro-ecosystem modelling applications could be extended to similar agro-ecological regions of the world, with the audience playing a crucial role in this extension and in improved understanding and calculating water-regulating agro-ecosystem services.

HIGHLIGHTS

- Study illustrated the use of agro-ecosystem models to simulate water regulating services.
- Application of developed infiltration models is demonstrated for a variety of soils.
- Simulated groundwater recharge by IPGRS model ranged from 83.0 to 90.2% of runoff.
- Simulation of soil erosion by a derived model ranged from 0.09-3.83 t ha^{-1} yr^{-1}

1 | INTRODUCTION

Globally, an agroecosystem is a dominant ecosystem covering about 40% of the earth's surface. It plays a crucial role in the overall development of the socio-economical conditions of a nation for the well-being of humans. An agroecosystem is the stronghold of a developing countries' economies. About 58% of India's population depends on agro-ecosystem services for their livelihoods. Globally, an agroecosystem demonstrates significant structural and functional disparities due to varied climatic, socioeconomic and cultural conditions that represent them. The functioning of the agro-ecosystem is an omnibus of a variety of components, including crops and cropping systems, tree-grass association, agri-horti and agri-silvi systems, pasture systems, and home gardening.

Agroecosystem service is defined as benefits, including tangibles and intangibles, provided by an agroecosystem for the human and society's well-being and country. Traditionally, the agroecosystem is primarily considered a provisioning services source for using products and by-products from the agricultural system. In addition to provisioning services, a variety of ecosystem services from agro-ecosystem services are documented, including regulating, cultural and supportive services (Fig.1). Agro-ecosystem provisioning services are the most visibly recognizable of all types of ecosystem services as they provide direct products to the people that can be used and monetized. Agro-ecosystem provisioning service offers products that include 4-Fs (food, fodder, fiber, and fuel) and supplementary harvestable produce. The regulation service regulates important components of ago-ecosystem processes, including hydrologic and climatic regulation. Hydrologic regulation agroecosystem services are associated with the movement and storage of water in terms of quantity. It impacts hydrological processes like runoff, infiltration, groundwater recharge, evaporation, evapotranspiration, and hydrologically linked natural vulnerabilities/ hazards (i.e. droughts and floods), irrigation and drainage as agricultural water management practices, water decontamination, and treatment of wastewater. It also affects land degrading processes, including soil erosion, loss of soil organic matter, carbon and nutrients from water, acidification salinization, and biodiversity. Supporting service refers to the fundamentals of soil and plant production processes, which include soil formation and structures, nutrient supply and cycling, natural pest and disease control, photosynthesis, and pollination. These are vital for providing provisioning ecosystem services. Cultural ecosystem services refer to non-material benefits gained from ecosystems, such as aesthetics, scenic beauty, inspiration, education, recreation, tourism, and traditional uses. The interactions between / amongst the agro-ecosystem services are highly multifaceted and complex and depend on interconnected and multiple ecosystem services. Simultaneously, it is accountable for altering or changing several ecosystems and their associated services and habitats.

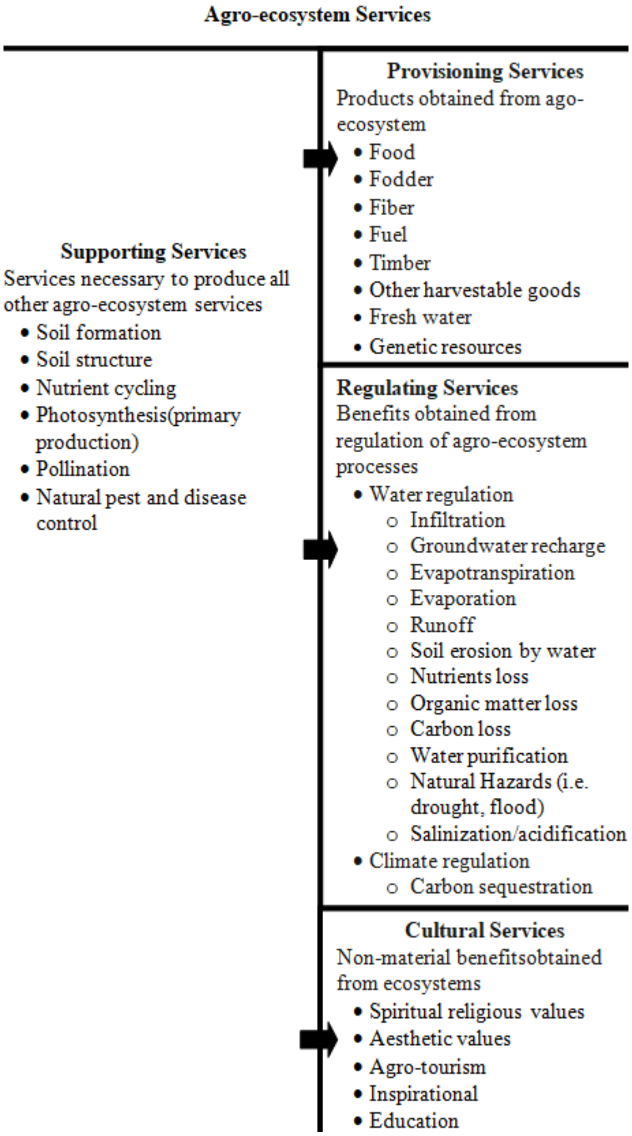


FIGURE 1 **Eco-system services made available by an agro-ecosystem**

Water is one of the most indispensable components for the functioning of an agro-ecosystem. Assessment and a better understanding of water-regulating agro-ecosystem services enhance the 4Fs and energy security through water management and help tackle water security problems. The objective of this paper is not to present the minutiae of the water-related agroecosystem services models but to demonstrate the applicability of different models developed in India for quantifying and predicting the water-regulating agroecosystem services under Indian conditions. Water is central to sustaining and supporting human and society's well-being. The paper focuses on the water-regulating services of the agroecosystems, mainly water movement and storage.

2 | AGRO-ECOSYSTEM SERVICES MODELING

An agroecosystem is a more complex and composite ecosystem due to several driving forces. These include the growing population and their demand for agroecosystem services, dwindling per capita agricultural lands of agro-ecosystems for intensifying the provisioning of agro-ecosystem services, changes in land use production system, and mounting pressures on natural resources for their sustainable uses. To overcome these varying and numerous problems of agro-ecosystem, there is growing interest in applying agro-ecosystem models in recent years. The agroecosystem models are necessary for increasing basic scientific understanding of agroecosystem components and interactions of the components, which assesses the production potentiality of the agroecosystem. Agro-ecosystem models also help to the decision and policymakers and ecosystem managers for screening the potential risk or vulnerable areas and identify the best management practices (BMPs) to maximize the profitability and sustainability of the agro-ecosystem for maintaining food water and energy security and better quality of environment.

2.1 | Agro-Ecosystem Models

Agro-ecosystem model is a simplified description of a complex agro-ecosystem that simulates/reproduces the temporal and/or spatial response of the agro-ecosystem. Agro-ecosystem models are either explanatory or descriptive. A descriptive model uses one or more mathematical equations based on experimental data to simulate the behaviour of a system. Explanatory models are used to model the system's process(s) and mechanics. These models include different combinations of mechanistic and functional model components. Explanatory models help to amplify the basic and better scientific understanding of the ecosystem. Mechanistic models are used to model basic mechanisms of plant and soil processes to simulate specific outcome (s). These are usually based on the agroecosystem's hypothesized and / or known physical, chemical, and biological processes. They are often used to understand specific processes and interactions better. Richards and Green-Ampt model for water movement in the soils are examples of mechanistic models in agro-ecosystem. Functional models use simplified approaches to simulate complex processes. Penman-Monteith or Priestley-Taylor models for simulation of potential evapotranspiration and radiation use efficiency models are some examples of functional models. The models use much less input data than mechanistic models, making them more simple and useful for those unfamiliar with the biophysical processes involved in the simulations**.** Functional-type models are now normally used in the DSSs (decision support systems). Dynamic system (DS) models have a mathematical function(s) with time-based on physical law governing the system that describes the future and change in response of the system with time by external forces such as management practices, climate, etc. The DS models may have mechanistic and functional components. Good examples of the DS Models for cropping systems are APSIM, CROPSYST, and EPIC. The agro-ecosystem models have been developed at field, farm, regional, national, and global scales. The users of the agro-ecosystem model ranged from farmers to policymakers interested in improving decisions and policies from the field to national and global levels.

3 | MODELING OF WATER-REGULATING AGRO-ECOSYSTEM SERVICES

Water movement processes in an agro-ecosystem involve surface runoff, infiltration [i.e. movement of water into the soil and its subsequent release to the atmosphere as evaporation from soil and transpiration from the plants (i.e. evapotranspiration)], groundwater recharge, and evaporation from the water surface. Water movement as surface runoff with a velocity greater than erosive velocity causes soil erosion and soil organic matter, nutrients, and carbon stock losses. To characterize and simulate water-regulating agroecosystem services, modelling these water movement regulating services is paramount. The paper herein discusses the principal applications of a few water-regulating agro-ecosystem models developed in India for some essential water-regulating service processes such as infiltration, potential groundwater recharge, surface runoff, water storage and soil erosion in agro-ecosystem under Indian conditions.

3.1 | Infiltration

Infiltration is one of the essential components of the agro-ecosystem that involves the entrance of the water from the soil surface into the soil profile and subsequent movement of this water through the unsaturated zone below the plant root zone as potential recharge/deep percolation and finally joins the groundwater table as groundwater recharge. The infiltration process in an agro-ecosystem is controlled by rainfall characteristics (i.e. intensity and duration), land slope (uniform and non-uniform), land use systems (agriculture, fallow, vegetation, pasture and forest), soil properties (i.e. moisture content, texture, layers, and surface sealing and crusting), movement and entrapment of soil air, plant density/architecture (i.e. broad or close spaced), and amount of litter at the soil surface and below the surface. The management practices of agroecosystems (i.e. tillage practices, mulch, manure, etc) and carbon stocks / pools also drastically alter the infiltration process. The agroecosystem has a higher rate of infiltration and cumulative infiltration than that of the fallow land ecosystems, and it tends to increase soil moisture status in the soil profile and groundwater recharge in the aquifers and reduce the peak flow and, consequently, floods.

Numerous infiltration models have been developed in the past and used to assess the infiltration behaviour of the upper soil layer in agro-ecosystems at a point scale. These models are classified as empirical, semi-empirical and physically based infiltration models. The empirical and semi-empirical infiltration models include Kostiakove, Holtan, Horton, and Philip models, that were developed based on laboratory or field experiment data and utilized simple mathematical expressions/equations. These models are not capable to explain the infiltration process fully. On the other hand, the physically based infiltration models explain the infiltration process substantially. The Green-Ampt (GA) and Richards models are the most widely and commonly used process-based infiltration or water flow models. Richards' model mingles the Darcy equation with the continuity equation and includes a sink term for soil water extraction by the root systems. Richards' model is solved by means of an iterative implicit numerical technique with fine discretization in both the space and time. Richards' and Richards' based modelling codes are still inappropriate for all soil types (principally soils with high clay or organic matter). However, the implicit GA model and its several modifications in explicit GA (Ali *et al.*, 2016) are extensively employed to simulate 1-D infiltration into various soils due to their simplicity and excellent field performance.

Ali and Islam (2018) have recently derived a simple and accurate explicit GA model for the implicit GA equation employing a two-step curve-fitting approach. The developed implicit model matched well with the implicit GA model (Fig. 2) with a MPRE (maximum percent relative error) of 0.012 and 0.146% for the dimensionless rate of infiltration and cumulative infiltration, respectively, and respective, PB (percent bias) of 0.0005 and 0.070. Field applications of the developed model over various soils showed its potential for application with MPRE ≤ 0.110% and PB ≤ 0.080 for infiltration rate and MPRE ≤ 0.130% and PB ≤ 0.050 for cumulative infiltration. Unlike following an iterative or trial and error method, as in the case of the implicit GA model, the developed model offers an explicit expression/equation without restriction to infiltration period and water depth in an agro-ecosystem. The derived explicit models for infiltration rate and cumulative infiltration are defined as:

$$F(t)=\frac{s^2}{2K_s}\left\{t^*+2.5009\ln\left[1+0.5833\sqrt{t^*}\begin{bmatrix}0.9723+0.0117\left[1-\mathrm{Exp}\left(-27.36\,t^*\right)\right]\\+0.0162\left[1-\exp\left(-2.5168\,t^*\right)\right]\end{bmatrix}\right]\right\} \quad ...(1)$$

$$\text{and}\quad f(t)=K_s\left[1+\frac{\eta_f\left(H+\psi_f\right)}{F\left(t^*\right)}\right] \quad ...(2)$$

$$\text{In which, } t^*=\frac{K_s t}{\eta_f\left(H+\psi_f\right)}=\frac{2K_s^2\,t}{s^2} \quad ...(3)$$

Where F(t) = cumulative infiltration at time, t [L]; f(t) = rate of infiltration at t [LT^{-1}]; t is the time [T]; t^* = dimensionless time [-]; K_s = saturated hydraulic conductivity of transmission zone [LT^{-1}]; H = depth of water over soil surface [L]; ψ_f = suction head / negative pressure head at wetting front [L]; η_f = fillable porosity [-] and equal to θ_s- θ_i; in which θ_i = initial volumetric moisture content [dimensionless]; and θ_s = total porosity (i.e. volumetric water content at near or fully saturation) [dimensionless], and s = sorptivity parameter [L T$^{-1/2}$].

Ali *et al.* (2013) also derived a generalized model for simulating the length of advancement of the wetting front (L_f); consequently, cumulative infiltration ($=\eta_f L_f$) and infiltration rate {= K_s [$1+\eta_f(H+\psi_f)/L_f$]} For the constant depth of water depth by replacing the logarithmic term of the implicit GA model with sequential segmental second-order polynomials. The developed model is simple in nature and has no restriction to infiltration time and water depth, alike the explicit GA model of Ali and Islam (2018). However, the model has higher errors than the Ali and Islam (2018) model, with MPRE of 3.21 and 11.43% for the dimensionless infiltration and cumulative infiltration rate, respectively, and the respective PB of 0.0005 and 0.070%. The model's validity has also been tested with the field experiment data, which compare well with field data. The model for the L_f is defined as:

$$L_f(t) = \left(H+\psi_f\right)\left[\sqrt{\frac{F_1 K_s}{\eta\left(H+\psi_f\right)}\,t + F_2} + F_3\right] \quad ...(4)$$

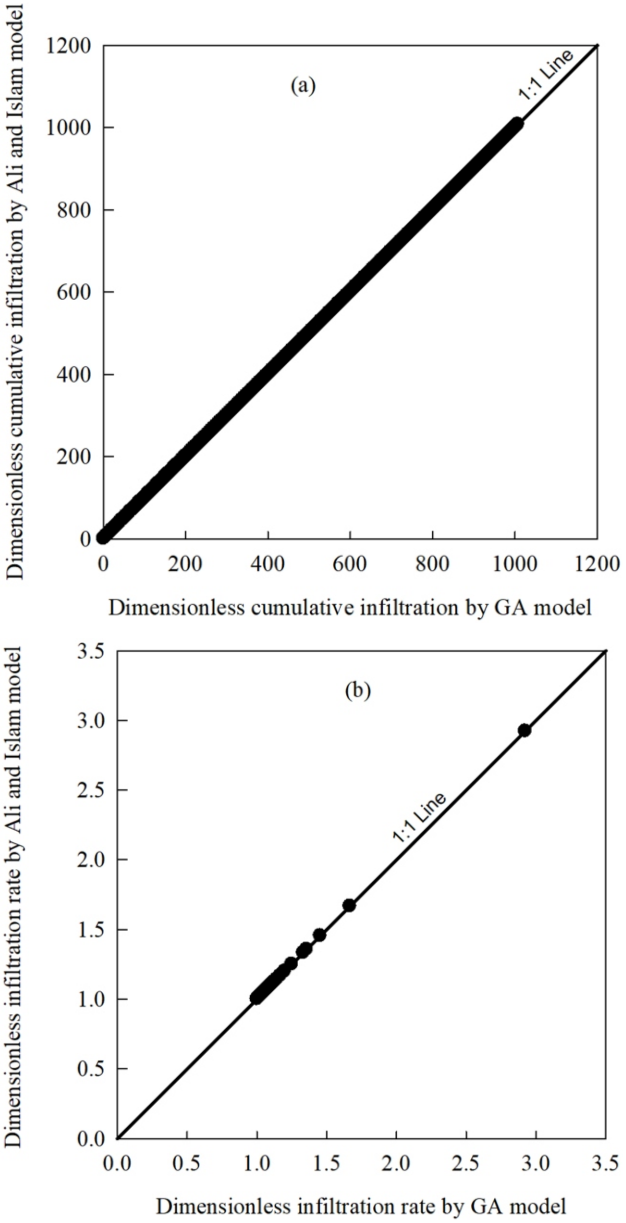


FIGURE 2 **Visual performance of dimensionless: (a) cumulative infiltration, I*(t*), and (b) infiltration rate, I*(t*) simulated by the derived explicit model and implicit GA model**

Where, $L_f(t)$ = length of advancement of the wetting front at t [T]; F_1, F_2 and F_3 = model coefficients for different ranges of dimensionless length of advancement of wetting front.

Application of the model of Ali *et al.* (2013) also suggested that the time delays for wetting front to reach shallow depth to water table (1-5 m) for a constant water depth of 2 m ranged between 1 hr and 13 days in most of the soils except medium and fine texture soils and from 1 to 135 days in all textural soils except fine texture soils for medium depth to water table (10-25 m). For larger depths to water table (≥ 50 m), time delays were from 1 month to several months in most soils except for very coarse textures such as loamy sand and sand.

Ali and Ghosh (2016) developed an infiltration model and used it to estimate the cumulative infiltration rate under variable water depths by modifying the GA equation. The derived models for cumulative infiltration and infiltration rate are:

$$F(t)=\eta\left\{L_f(t-\Delta t)+[H(t-\Delta t)+\psi]\left\{\sqrt{\frac{F_1 K_s}{\eta\,[H(t-\Delta t)+\psi]}\,t+F_2}-\sqrt{\frac{F_1 K_s}{\eta\,[H(t-\Delta t)+\psi]}(t-\Delta t)+F_2}\right\}\right\} \qquad ...(5)$$

and

$$f(t)=K_s\left[1+\frac{H(t)+\psi_f}{L_f(t-\Delta t)+[H(t-\Delta t)+\psi]\left\{\sqrt{\frac{F_1 K_s}{\eta\,[H(t-\Delta t)+\psi]}\,t+F_2}-\sqrt{\frac{F_1 K_s}{\eta\,[H(t-\Delta t)+\psi]}(t-\Delta t)+F_2}\right\}}\right] \qquad ...(6)$$

Where, H(t) = depth of water at t [L]; Δt = change in time from t to t-Δt [T]; and other terms are defined earlier.

The models provide a solution for estimating infiltration with no restrictions on the infiltration time, water depth, and soil types, unlike the rigorous solution of the Richards model. Performance of the derived model compared well with Richards's (Richards, 1931) and Warrick *et al*. (2005) models with published field experiment and laboratory data (Fig. 3). Comparative studies of the model for variable water depth over variety of soils demonstrated its capability for their field application to estimate potential infiltration or groundwater recharge, evaluate the performances and Design of the WHSs (water harvesting structures), AGR (artificial groundwater recharging) facilities, irrigation systems, and resolving solute transport problems.

3.2 | Potential Groundwater Recharge

Groundwater recharge (GR) is the process of replenishing groundwater storage. The GR process has two distinguished mechanisms: one is regarded as the wetting front advance-

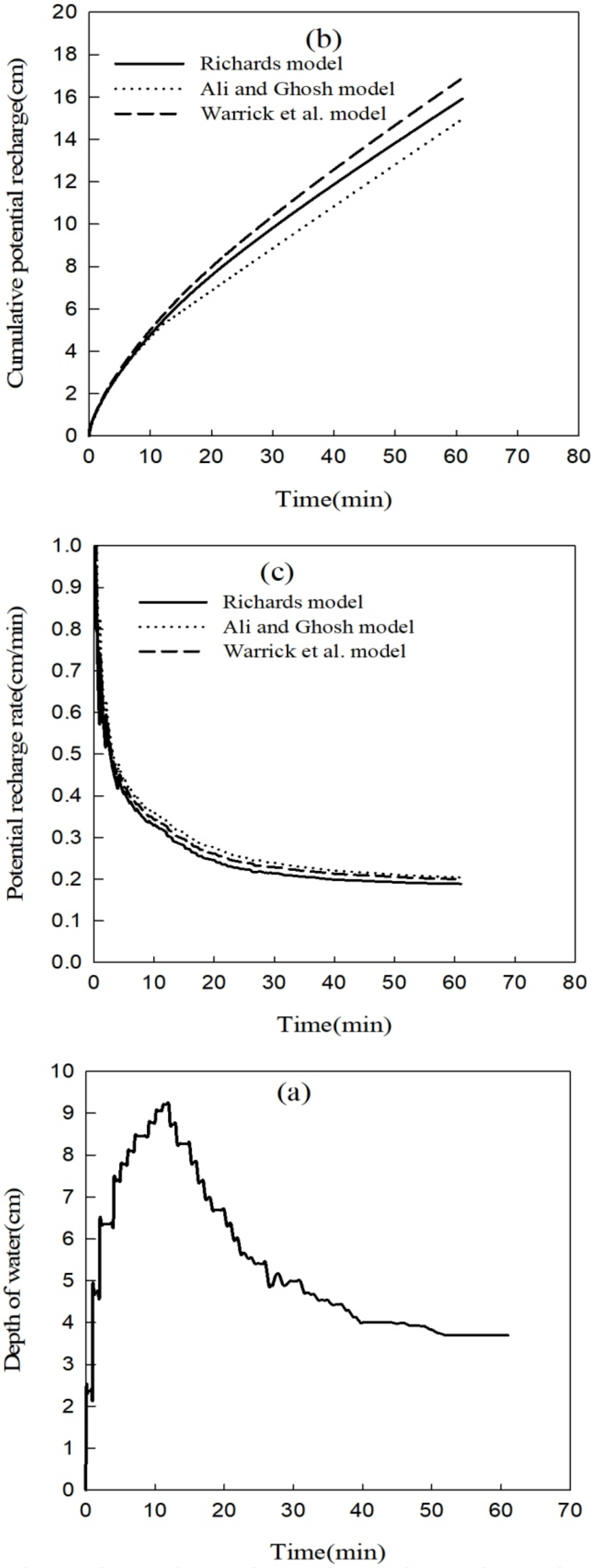


FIGURE 3 **Response of time-variant: (b) cumulative potential recharge, (c) potential recharge rate from irrigation basin over superstition sand under varying depths of ponding, and (a) depths of ponding**

ment by downward movement of water through the unsaturated zone and continues till the wetting front touches the water table, known as potential infiltration/groundwater recharge; and the other one is subsequent recharge after the wetting front touches the groundwater table, known as actual groundwater recharge or groundwater recharge (Ali *et al.,* 2013). The groundwater table progresses after the actual groundwater recharge process starts. Hydrogeological and climatic conditions control groundwater recharge amount and timing. The key factors affecting the GR are rainfall characteristics (amount and duration), ponding depth over soil surface, soil type, vegetation characteristics, etc. The influx of the potential groundwater recharge to the groundwater table depends on unsaturated zone processes and depth and the capability of the zone of saturated to allow it.

Several empirical and physical-based models of varying complexity are exited to quantify potential and actual groundwater recharge. The process-based potential groundwater recharge models are implicit and explicit GA, and Richards' and Richards' based numerical modelling codes such as HYDRUS, UNSAT-H, and TOUGH2. The models for estimation of actual groundwater recharge are MODFLOW and its variants, i.e. Visual MODFLOW, PMWIN-Processing Modflow for Windows, HYDRUS-MODFLOW, FEFLOW-Finite Element subsurface FLOW System, SWAP (Soil-Water-Atmosphere-Plant) and GMS-Groundwater Modelling System.

Ali and Ghosh (2019) developed the IPGRS (Integrated Potential Groundwater Recharge Simulation) model using the modified GA equation for variable water depth in the water balance equation. The IPGRS model estimates time-varying potential groundwater recharge rates under variable water depths from AGR facilities and WHSs in an agro-ecosystem. The parameters of the IPGRS model are time-variant rainfall, runoff, water evaporation, surplus/outflow, and length of advancement of the wetting front into the soil. The model also considered soil-related physical parameters, namely, saturated hydraulic conductivity, fillable porosity of the soil material, and suction head/negative pressure head at the wetting front. The IPGRS model is process-based and holistic in nature, easy to use and capable of simulating potential groundwater recharge rates with reasonable accuracy. The IPGRS model has broad field applications and can successfully be extended to estimate potential groundwater recharge rates from AGR facilities and WHSs of any size and shape situated at any location or geographical region of India and elsewhere. The IPGRS model is defined (Ali *et al.*, 2015; Ali and Ghosh, 2019):

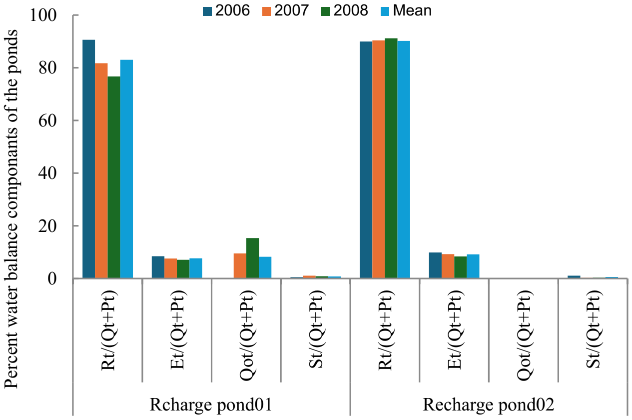
$$R_p(t)=\frac{K_s}{\left[L_f(t)A_{ws}(t)+K_sA_{rs}(\bar{t})\Delta t\right]}\left\{\begin{aligned}&H(t-\Delta t)A_{ws}(t-\Delta t)+\left[Q(t)A_w+P(t)A_s-E(t)\bar{A}_{ws}(t)-Q_0(t)\right]\Delta t\\&+\left[L_f(t)+\psi_f\right]A_{ws}(t)\end{aligned}\right\}\qquad\ldots(7)$$

In which the $l_f(t)$ is:

$$L_f(t)=L_f(t-\Delta t)+\left[H(t-\Delta t)+\psi\right]\left\{\begin{aligned}&\sqrt{\frac{F_1K_s}{\eta\left[H(t-\Delta t)+\psi\right]}\,t+F_2}\\&-\sqrt{\frac{F_1K_s}{\eta\left[H(t-\Delta t)+\psi\right]}(t-\Delta t)+F_2}\end{aligned}\right\}\qquad\ldots(8)$$

Where, $R_p(t)$ = potential recharge rate AGR/WH structure at time, t [LT^{-1}]; $Q_i(t)$ = runoff into structure at t [LT^{-1}]; $P_i(t)$ = rainfall over the structure at t [LT^{-1}]; $E_p(t)$ = evaporation from the structure at t [LT^{-1}]; $Q_o(t)$ = outflow rate of surplus runoff from the structure at t [L^{3T-1}]; H(t) = water depth at t [L]; H(t-Δt) = water depth at t-Δt [L]; Δt = time interval [T]; L_f length of advancement of wetting front at t [L]; $L_f(t-\Delta t)$ = length of advancement of wetting front at t-Δt [L]; K_s and ψ_f = defined earlier; A_w = AGR/WH structure's catchment [L^2]; A_t = surface area of the structure at top [L^2]; $\bar{A}_{ws}(t)$ = average water storage surface area between time t-Δt and t [L^2]; $\bar{A}_{rs}(t)$ = average wetted planner area for recharge at time t [L^2].

Application of derived IPGRS model in BK watershed, Rajasthan, India showed that on average, 83 to 90% of stored runoff in the recharge ponds added as potential groundwater recharge into aquifer underneath recharge ponds. Evaporation losses from recharge pond varied between 8% and 9% of stored runoff. Surplus flows from the ponds and stored runoffs in recharge ponds at the end of simulation periods ranged from 0 to 8% and 0.6 to 0.8%, respectively (Fig. 4).



This is the ratio of the total volume of water recharged into the aquifer, R_t, to the total volume of inflows, which is the sum of the volume of runoff into the pond and the volume of rainfall directly over the pond, (Q_t+P_t); $E_t/(Q_t+P_t)$ the ratio of the total volume of water loss by evaporation, Et to the total volume of inflows; $Q_{ot}/(Q_t+P_t)$ is the ratio of the total volume of outflows from the pond, Q_{ot}, to the total volume of inflows, and is the ratio of the total volume of water remaining as pond storage at the end of the simulation period, S_t, to the total volume of inflows.

FIGURE 4 Partition factors of the water balance components (percent) for the recharge ponds during the simulation period (2006-08)

3.3 | Surface Runoff

Runoff yield from an agro-ecosystem provides water security to the water resources such as surface and groundwater through infiltration, interflow and base flow, and groundwater recharge. Assessment/estimation of surface runoff yield in an agroecosystem is a highly complex problem. It is influenced by several characteristics of the agro-ecosystem, including topography, morphology, antecedent soil moisture condition, land use land covers, and cover conditions, rainfall characteristics (i.e. amount, intensity and duration) and conservation measures density (Ali and Singh, 2001; Ali *et al*., 2010; Ali *et al*., 2017). The need to better understand the runoff process and its quantification is further aggravated due to climatic variability and change and the desire to develop climate-resilient agro-ecosystem technologies / practices. Several runoff simulation models based on statistical, conceptual, physical, and combination approaches have been derived and used in the past according to the need and availability of data for better understanding and predicting the highly non-linear, dynamic and complex runoff process worldwide. The commonly used methods include SCS-CN (Soil Conservation Service - Curve Number), HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System), CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems), KINEROS (Kinematic Runoff and Erosion Model), SVAT (Soil-Vegetation-Atmosphere Transfer), SWAT (Soil Water Assessment Tool), and PRMS (Precipitation Runoff Modeling Systems).

Ali *et al.* (2010) derived a rainfall-runoff model analogous to the SCS-CN model based on the NAPI (Normalized Antecedent Precipitation Index) using the water balance concept in an agroecosystem. The model is mathematically defined as:

$$Q = \frac{P\left(-bP + c\,NAPI + a\right)}{\left[\left(-bP + c\,NAPI + a\right) - 1\right]} \quad \text{valid for } P > 0 \qquad \ldots(9)$$

Where, Q = runoff for corresponding rainfall, P [L]; NAPI = normalized antecedent precipitation index [-]; *a* [-], b [L^{-1}], and c[-] are model parameters related to a specific agro-ecosystem / watershed.

The developed rainfall-runoff model is simple in mathematical nature, user-friendly, and minimum data driven. Only rainfall and rainfall-derived NAPI is required if model parameters (i.e. a, b, and c) are known previously for the given agroecosystem. The derived rainfall-runoff model is a handy runoff tool for simulating runoff yields in the agro-ecosystems, and has broad applicability. The developed model could also be employed for runoff assessment / estimation from gauged and un-gauged agroecosystem / watersheds with the least data, i.e. rainfall only. The surface runoff predicting the potentiality of the developed rainfall-runoff model has also been compared with the SCS-CN model. Results revealed that the developed rainfall-runoff model matched well with the SCS-CN model (Fig. 5), which is a comparatively large data-driven model (i.e. AMC (antecedent moisture condition), and information on land use cover, conservation / treatment practice, hydrological oil group and hydrologic condition). The developed runoff model was also applied in a small agricultural watershed, and two ravine watersheds located in a semi-arid agro-ecosystem of Rajasthan, India (Fig. 6). The assessed runoff yield for the ravine and cropped areas of the agro-ecosystems varied

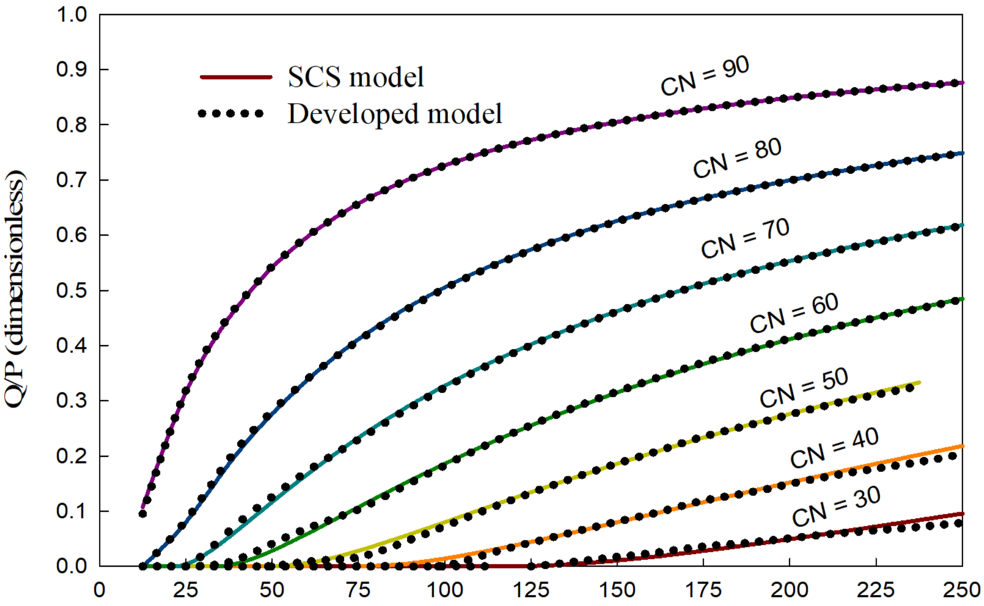


FIGURE 5 **Visual evaluation of the derived Q/P profiles by the SCS-CN model for the P and different CN-values with the corresponding profiles of the derived rainfall-runoff model**

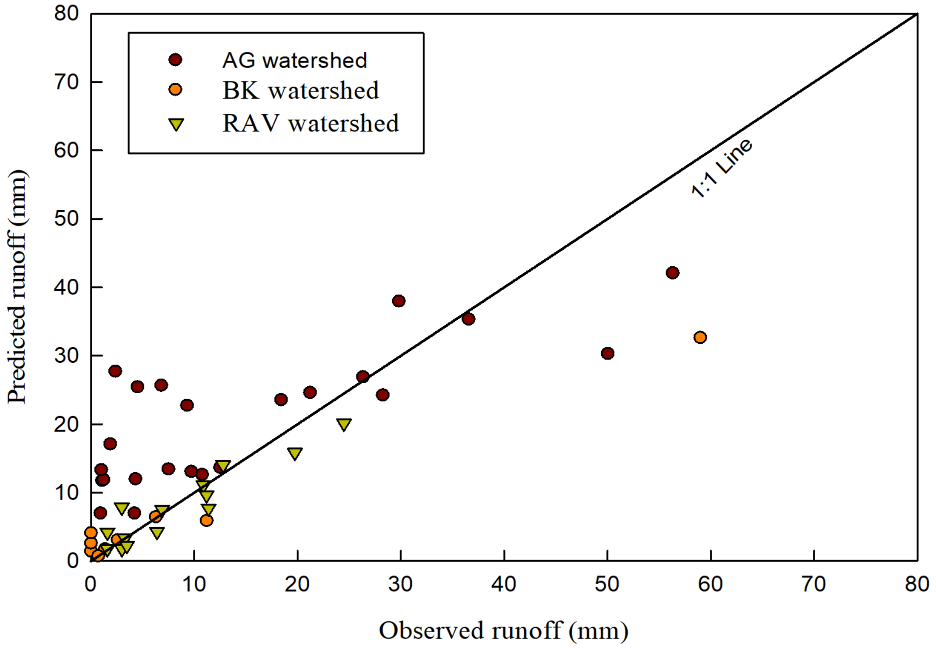


FIGURE 6 **Visual judgment of the simulated and observed runoffs by the derived rainfall-runoff model in three small watersheds in the agro-ecosystems of a semi-arid region of India**

between 10 and 20% of the rainfall over the agro-ecosystems.

A rainfall-runoff model for un-gauged watersheds for the agro-ecosystem has also been developed correlating the model parameters of the un-gauged and gauged watersheds of the agro-ecosystems and mathematically defined (Ghosh *et al.*, 2021) as:

$$Q^* = \frac{P\left(-b^* P + c^* NAPI + a^*\right)}{\left[\left(-b^* P + c^* NAPI + a^*\right) - 1\right]} \quad \text{valid for } P>0 \qquad ...(10)$$

Where *a**, b*, and c* are the un-gauged watershed model parameters; others are defined previously.

The un-gauged watershed model parameters are defined as:

$$a^* = a \times CGI \times CLI;\ b^* = b \times CGI \times CLI;\ \text{and } c^* = c \times CGI \times CLI \qquad ...(11)$$

In which CGI and CLI are the cumulative geomorphologic indexes and cumulative land use and land cover index, respectively, and these are defined as:

$$CGI = \sum_{i=1}^{n} IOP_i^G = \sum_{i=1}^{n} RW_i^G \left(\frac{GP_i}{GP_i^*}\right) \qquad ...(12)$$

$$CLI = \sum_{i=1}^{j} IOP_i^L = \sum_{i=1}^{j} RW_i^L \left(\frac{AL_i/AL}{AL_I^*/AL^*}\right) \qquad ...(13)$$

Where, IOP^G_i = index of the ith geomorphologic parameter [-]; RW^G_i (= w^G_i/W^G) = relative weightage of the ith geomorphologic parameter [-]; w^G_i = weightage of the ith geomorphologic parameter [%]; W^G = sum of the all selected geomorphologic parameter [%]; GP_i = value of the ith geomorphologic parameter of the gauged watershed[unit of parameter]; GP^*_i = value of the ith geomorphologic parameter for the un-gauged watershed[unit of parameter]; IOP^L_i = index of the ith land use and land cover (LULC) class[-]; RW^L_i (= w^L_i/ W^L) = relative weightage of the ith LULC class [-]; w^L_i = weightage of the ith LULC class [%]; W^L = sum of the all LULC classes [%]; AL_i = area of the ith LULC class of the gauged watershed [ha]; AL = total area of the LULC classes of the gauged watershed[ha]; AL^*_i = area of the ith LULC class of the un-gauged watershed [ha]; AL^* = total area of the LULC classes of the un-gauged watershed [ha]; and i = integer, i = 1, 2, 3, ...n/j.

The values of the w^G_i or w^L_i are arbitrarily chosen based on the importance of selected geomorphologic parameters or LULC class, and $0 < w^G_i < 100$, $0 < RW^G_i < 1$, $0 < w^L_i < 100$, and $0 < RW^L_i < 1$. The values of the W^G, W^L, RW^G and RW^L are:

$$W^G = \sum_{i=1}^{n} w_i^G = 100; \qquad RW^G = \sum_{i=1}^{n} RW_i^G = 1 \qquad ...(14)$$

$$W^L = \sum_{i=1}^{j} w_i^L = 100; \qquad RW^L = \sum_{i=1}^{j} RW_i^L = 1 \qquad ...(15)$$

The derived model was tested and validated for un-gauged (Rahatgarh, 1180 km^2) and gauged (Korwal, 2806 km^2) watersheds by utilizing the 339 rainfall-runoff events that occurred in 18-year periods (1990-2007). The field application exhibited a close match between the observed and computed values of runoffs from an un-guaged watershed. The derived model parameters a^*, b^* and c^* for the un-gauged watershed were - 0.2136, 0.00202, 0.02313, respectively, and -0.21038, 0.00199, and 0.02279, respectively, for the a, band c model parameters for the gauged watershed.

3.4 | Water Storage

Natural and anthropogenic surface water bodies in the agro-ecosystem play a fundamental role in maintaining an ago-ecosystem's hydrological, environmental and ecological balance, primarily by increasing or improving water availability for longer periods. The time-varying availability of water in surface water bodies also plays a crucial role in coordinated and comprehensive planning for the utilization of surface water resources in the agro-ecosystems. Numerous models have been derived and employed in the past for simulating water depth or volume of water in surface water bodies. These include dynamic linear predictor models, non-linear intelligence models, and modelling codes, i.e. SPAW (Soil-Plant-Air-Water), etc.

The HWDS (Holistic Water Depth Simulation) model was developed by Ali et al. (2015) by integrating the derived models for the rainfall-runoff, length of advancement of the wetting front and evaporation in the water balance equation of the surface water body. Alike IPGRS model for assessing the potential groundwater recharge, the developed HWDS model also take account of the time-variant rainfall, runoff, surface water evaporation, outflow and length of advancement of wetting front; saturated hydraulic conductivity, fillable porosity of the surface water body's bed material and suction head as model parameters. The derived HWDS has been defined mathematically (Ali *et al.*, 2015; Ali, 2016):

$$\begin{aligned} H(t) = {} & H(t-\Delta t)\frac{A_{ws}(t-\Delta t)}{A_{ws}(t)} + \frac{\Delta t}{A_{ws}(t_i)}\Big[Q(t)A_w + P(t)A_s - E(t)\bar{A}_{ws}(t) - Q_0(t)\Big] \\ & - \frac{K_s\,\bar{A}_{rs}(t)\,\Delta t}{A_{ws}(t)}\left[1 + \frac{H(t)+\psi_f}{L_f(t-\Delta t) + \{H[t-\Delta t] + \psi_f\}\left\{\sqrt{\frac{F_1 K_s}{\eta\,[H(t-\Delta t)+\psi_f]}t_i + F_2} - \sqrt{\frac{F_1 K_s}{\eta\,[H(t-\Delta t)+\psi_f]}(t-\Delta t) + F_2}\right\}}\right] \end{aligned} \quad \ldots(16)$$

$$\text{and}\ \ V(t) = H(t)\,\bar{A}_{ws}(t) \quad \ldots(17)$$

Where V(t) = volumetric water availability in a surface water body at time t_i [L^3]; $\bar{A}_{wa}$ = average water storage area at t_i [L^2] = $0.5[A_{ws}(t) + A_b]$; and A_b = water body's bottom surface area [L^2]; and rest of the terms = defined prior.

The derived HWDS model is process-based and holistic in nature, user-friendly, and capable of predicting the time-varying depth of water and consequent volumetric water availability in the surface water bodies in the agro-ecosystem with reasonable accuracy. The HWDS model has broad field applicability and could successfully be extended to assess water availability in a water body of any size and shape in any location or geographical region in India and elsewhere. The simulated time-varying water availability employing the derived HWDS model matched well with the ponds data of the BK watershed in an agro-ecosystem in Rajasthan, India (Fig.7). The predicted time-varying water availability in the pond#1 and Pond #2 is observed higher in July, August and September, and almost empty in the November and December during the study period.

3.5 | Soil Erosion

Soil erosion by water in agroecosystems is a significant threat and impacts society and the economy to a greater extent in the agroecosystems of the world. Soil erosion in the agro-ecosystems causes on-site problems with the removal of the significant top productive soil layer, losses of agro-ecosystem land, soil organic matter and nutrients, deterioration of soil properties (i.e. physical, chemical and biological) and diminution of agro-ecosystem productivity and production as soil erosion diminishes or reduces soil nutrients, soil water storage capacity and impacting crop growths. Soil erosion also fetches off-site damages, including sediment deposition or silting of the water bodies (i.e. pond, reservoir, channel / stream, river, etc.) and surface water quality by agrochemicals and colloid-facilitated transport. The rate of soil erosion is affected by various factors, such as anthropogenic factors (i.e. intensification of the agroecosystem, land use changes and human activities) and climatic factors, mainly rainfall characteristics (amount, intensity and duration). Changes in rainfall characteristics and spatio-temporal distribution patterns of rainfall mainly cause the impacts of change in the rate of soil erosion. Several investigators assessed the soil erosion problems and their effect on the crop and cropping systems in the different agroecosystems of India (Ali and Sharda, 2005; Sharda and Ali, 2008).

Ali *et al.* (2002) derive a very simple soil erosion model for predicting potential soil erosion from an agro-ecosystem. The developed soil erosion model is:

$$Y = a\,(RKC)^b \quad \ldots(18)$$

Where Y = annual soil loss [t ha^{-1}]; R = annual rainfall erosivity factor; K = soil erodibility factor [t ha^{-1} unit of IE_{30}]; C = crop and cover management factor[-], and a and n = model parameters specific to the agro-ecosystem.

The developed soil erosion model has reasonable accuracy, is simple, user-friendly, and minimally data-driven. The soil erosion model has also been tested for different crops and cropping systems in the agro-ecosystem in the semi-arid region of India and recorded that the model

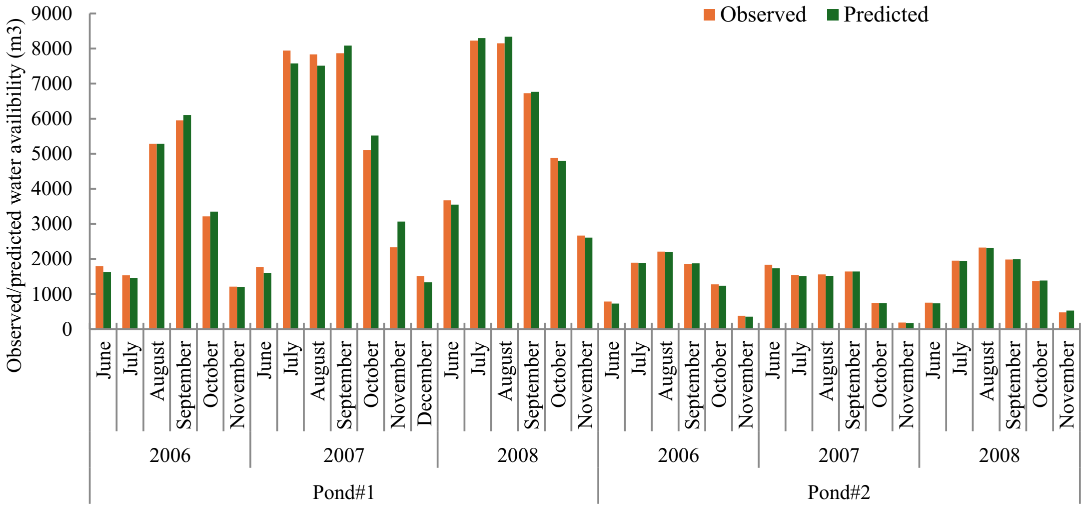


FIGURE 7 Visual comparison of the time-variant predicted and observed water availability by the derived HWDS model in pond#1 and pond#2 in an agro-ecosystem in the semi-arid region of India

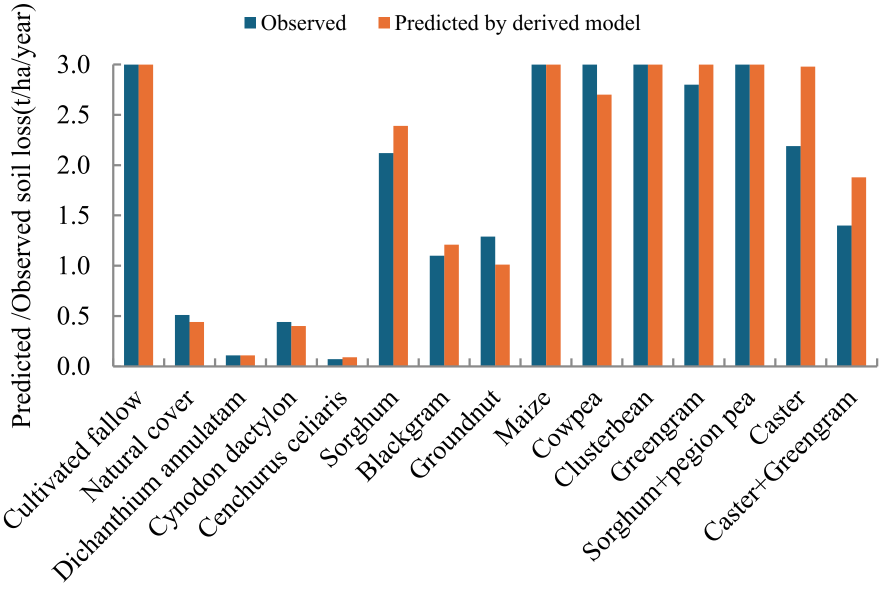


FIGURE 8 Visual comparison of the time-variant predicted and observed water availability by the derived HWDS model in pond#1 and pond#2 in an agro-ecosystem in the semi-arid region of India

performed well in the agro-ecosystem of India (Fig. 8). The simulated soil erosion employing the developed erosion model for the grasses (i.e. *Dichanthium annulatam*, *Cenchurus celiaris and Cynodon dactylon*), close growing crops (i.e. green gram, black gram, cowpea and groundnut), broad spacing crops (i.e. sorghum, maize, cluster bean and caster) and mixed crops (caster + green gram and sorghum + pigeon pea) system varied from 0.09 to 0.11, 1.01 to 3.05, 2.39 to 4.22, 1.88 to 3.83 t ha^{-1} yr^{-1}, respectively.

5 | CONCLUSIONS

Globally, the agroecosystem is a principal ecosystem, and it offers 4Fs (food-fodder-fibre-fuel) termed as provisioning ecosystem service for more than 7.7 billion human population in the world, which are indispensable to human well-being. Agroecosystems also provide an array of water-regulating and cultural agroecosystem services. These services depend on supporting ecosystem services offered by the agroecosystems. To better understand and quantify the unpredictability of agroecosystem services, agroecosystem prediction models have the potential to do it better. The study demonstrates the promising capability and applicability of some agroecosystem models in India for predicting the water-regulating agroecosystem services such as surface runoff, soil erosion, infiltration, potential recharge and water storage. Developed water-related agro-ecosystem simulation models have been successfully applied to the different agroecosystem services in India's agroecosystems.

The application of the derived infiltration model accurately predicted the time delays for the wetting front to reach depth to the water table in various soil textural classes. The simulated potential groundwater recharge from WHSs by the developed IPGRS model varied between 83 to 90% of stored runoff in the WHSs. Modelled agroecosystem surface runoff ranged from 10-20% of the rainfall. The derived model for soil erosion is effectively applied to different crops and cropping systems in the agroecosystems of India, and the mean annual soil loss is assessed as 0.09 to 3.83 t ha^{-1} yr^{-1}. These modelling studies for water-regulating agro-ecosystem services indicated that modelled values vary across the models and the land-use system within the agroecosystem. The developed models for water-regulating agroecosystem services offer valuable and important information for policy decisions on preparedness, adaptive planning, and preventive and conservation measures to mitigate the effects of climate variability and change on water-regulating ago-ecosystem services. In future, there is a need to develop evaporation and evapotranspiration water regulating and provisioning ecosystem service models for their better understanding of Indian conditions.

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DATA AVAILABILITY STATEMENT

Data used in the manuscript is with the author and may be supplied on demand.

CONFLICT OF INTEREST

There is no conflict of interest among the authors.

AUTHOR'S CONTRIBUTION

The author solely contributed to the manuscript.

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