Modeling Water Savings for Groundwater Irrigated Rice–Wheat Systems in Northwest India

Adapting the FAO56 methodology for a plot-level soil water balance analysis

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Abstract

The rice-wheat cropping system in northwest India's Haryana and Punjab states – a cornerstone of national food security and a key driver of India's position as a leading global rice exporter – has precipitated severe groundwater depletion due to intensive irrigation practices. This study examines the effect of water-saving strategies on groundwater decline in Karnal, Haryana, by evaluating their impacts on plot-level consumptive water use and non-consumptive losses. While modern established methods like direct-seeded rice (DSR), water conserving irrigation schemes like alternative wetting and drying (AWD), delayed transplanting, and short-duration rice varieties have been shown to reduce irrigation demand, their true water-saving potential remains unclear due to inadequate accounting of return flows that recharge aquifers. By adapting a python based implementation of the FAO56 methodology for paddy rice and non-standard irrigation practices, a systematic plot-level water balance analysis was carried out to quantify the effects of rice establishment methods (puddled transplanted rice [PTR] vs. DSR), planting dates, varietal durations, and irrigation scheduling on evapotranspiration (ET), irrigation requirements, and deep percolation in a rice-wheat rotation.

Key findings suggest that an ET reduction target of 10 % is required to halt the groundwater decline in Karnal, Haryana. While current best-practices DSR and AWD reduce irrigation requirements by up to 30 %, they have minimal effect on consumptive ET, and are not able to stem the groundwater decline. Conversely, delaying crop establishment by 20 days beyond what is commonly practiced, and using short-duration rice varieties can reduce ET by 15 to 20 %, offering real water savings at the cost of yield penalties. Optimized irrigation scheduling on the other hand only marginally reduces ET and faces adoption challenges due to operational complexity and risk. This underscores that sustainable groundwater use in northwest India is possible through a careful combination of policy, management and technological interventions that focus on reducing ET rather than just improving irrigation efficiency.

Disclaimer

To the best of my intentions, Artificial Intelligence (AI) was used as a tool to complement my research in accordance with the guidelines of Wageningen University and Research.

The generative AI models DeepSeek, ChatGPT and GitHub Copilot were used to assist with data analysis in R and troubleshooting the pyfao56 model. DeepSeek and ChatGPT were used to draft and provide feedback on certain sections of this thesis, as well as provide a cursory overview of certain concepts in the fields of soil physics and crop modeling. These tools proved indispensable for understanding the pyfao56 model code and helping me with structuring the additional code segments for the model.

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Contents

Chapter 1

Introduction

1.1 History and Context

As part of the Indo-Gangetic Plains, the region of North-West India is characterized by a monsoonal climate with high seasonal variation. Focusing on the states of Punjab and Haryana (bordering Pakistan and the Indian Himalayas), temperature differences of 40 °C between hot, humid summers and cold dry winters are common. In the months of May and June temperatures can reach over 45 °C, and cold nights in February can reach near freezing. The high spring temperatures drive extreme evaporative demand, peaking at $\sim$10 mm d^{-1} by early May. As a respite, the monsoon season (June–September) delivers 600 mm to 700 mm of rainfall, often in intense storms (Humphreys et al. 2010), with minimal precipitation throughout the rest of the year.

Situated just south of the Himalayan massif, the Indo-Gangetic Plains form a vast, flat alluvial landscape shaped by sediment deposition from the Ganges and Indus rivers and their tributaries. Over millennia, steady sediment deposition by these river systems has created deep phreatic aquifers (>200 m) with heterogeneous, layered sediment textures ranging from coarse sands to fine clays depending on past river flow paths (van Dijk, Densmore, A. Singh, et al. 2016; van Dijk, Densmore, Jackson, et al. 2020). Near major river courses such as the Yamuna in districts like Karnal, Panipat and Sonipat, soils are lighter (sandy loam, sand), and tend to transition to heavier textures (loam, clay loam) further inland.

The landscape and culture in Haryana and Punjab have been shaped by agriculture for millennia, where the ample monsoon rains would naturally inundate lower-lying areas and provide enough irrigation water for crop production (A. Singh et al. 2017). This changed in the mid-19th century under British rule when extensive publicly funded canal irrigation systems were introduced to protect against crop failure and stabilize production (Erenstein 2009). The onset of the green revolution of the 1960s then led to the replacement of traditional crops like pulses and millet by high-yielding rice and wheat varieties. To achieve food self-sufficiency the total cropping area was expanded and the cropping system was intensified. This transformation was enabled

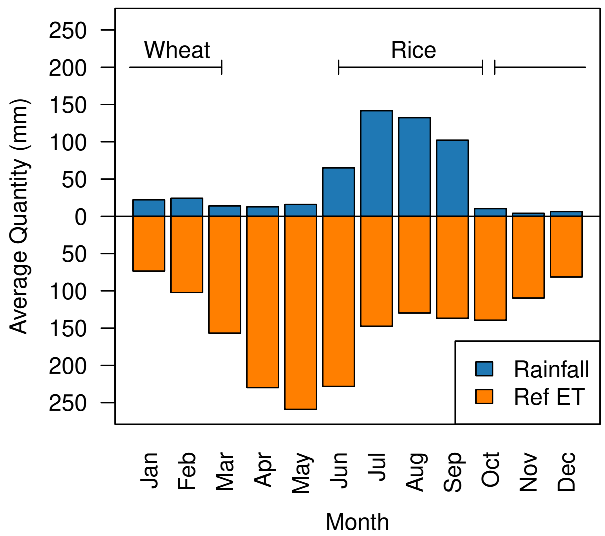

Figure 1.1: Long term (1989-2019) mean monthly rainfall, and reference evapotranspiration for Karnal, Haryana. Standard rice and wheat cropping seasons indicated as a reference. Data source: Lange et al. (2021)

by intensive irrigation, the introduction of chemical fertilizers, and mechanization alongside an uptake of groundwater pumping. This boosted productivity by almost 300% over the course of the green revolution(R. Singh 2000).

Due to extensive electrification efforts in the region and more general advances in pumping technology, groundwater had overtaken canals as the primary irrigation source by the 1980s (Erenstein 2009). By this time the cumulative percolation from the vastly inefficient canal irrigation schemes had raised groundwater levels from 40 m to less than 10 m below the surface in many regions (Hira et al. 1998), and farmers were able to capitalize on an easily accessible water resource that proved more flexible and reliable than erratic canal supplies. In 2010, in Punjab and Haryana about 85% of the land was used for crop production with most farmers growing two crops per year (avg. intensity 189%). Of this area 88% is used for rice and wheat. In the semi-arid climate, 95% of this cropland requires irrigation (Humphreys et al. 2010), and the system places huge demands on water resources. These intensive agricultural practices combined with the switch to groundwater as main irrigation source has led to alarming rates of groundwater depletion in certain regions of the Punjab and Haryana (Kumar Joshi et al. 2021).

1.2 Current Agricultural Practices

Because of its high water demand, rice is exclusively grown during the monsoon season (June to September) and wheat or other follow-up crops are grown in the dry season thereafter (October to March) (McDonald et al. 2022). Other popular crops beside rice and wheat include millet, cotton, maize, sugar-cane, various types of pulses, potatoes, and vegetables. India is the leading global exporter of Basmati rice and accounts for 25% (valued at $9.8 billion USD in 2022–23) of global rice production. Similarly, wheat exports to neighboring countries were valued at $1.5 billion USD during the year 2022–23 (APEDA 2023). Naturally, there is a great interest to maintain or even increase these figures.

Because the large water demand and widespread popularity of the dominant rice-wheat cropping system, the aim of this thesis is to gain understanding into the practices governing rice and wheat cultivation, as well as what adaptations to the system could help mitigate depletion of groundwater.

1.2.1 Rice Planting Methods

In northwest India farmers predominantly employ two rice establishment methods. The traditional approach, transplanted rice (PTR), involves creating a puddled field through repeated plowing and harrowing under flooded conditions to form a compacted plow sole at 45 cm to 50 cm depth, which allows for continuous flooding of the field during the rest of the growing season and significantly reduces water requirements. Twenty day old seedlings are then transplanted by hand into the flooded fields.

In contrast, direct-seeded rice (DSR), officially recommended since 2010 (PAU 2024), adopts mechanized seeding to directly drill-sow rice into dry non-puddled fields in rows, similar to other crops such as wheat or maize. This eliminates the need for nursery preparation and manual transplantation. While no water-retaining plow sole is established, the method is reported to offer advantages in labor efficiency and reduced water use (Mishra et al. 2017; Tripathi et al. 2016). The shift toward DSR also reflects broader agricultural mechanization and modernization efforts, though adoption rates remain low and are influenced by factors such as labor availability and government subsidies (Kaur et al. 2024).

1.2.2 Planting and Transplanting Dates

Over the last decades, the increasing reliance on groundwater irrigation has led to a decoupling of planting schedules from monsoon timing, enabling earlier cultivation. Farmer surveys conducted in Karnal, a district in Haryana, reveals nursery establishment as early as the first week of May (over 6 weeks before monsoon onset), with transplanting typically occurring a few weeks before the first heavy rains (unpublished data; IRRI-ISARC, 2024). Soon after the rice harvest, wheat is sown (1st week of November) and grows throughout the dry season when rainwater is scarce. Farmers are advised to harvest the wheat crop before April to avoid terminal heat stress (PAU 2023).

To curb groundwater depletion in the states of Haryana and Punjab, the Preservation of Subsoil Water Act (2009) prohibits rice transplanting before the 10th of June, and has since been extended to the 20th of June (Balwinder-Singh, McDonald, et al. 2019). The field data from Karnal shows the mean transplanting date was on June 20th in 2024, though DSR is not affected by this law and sown approximately 20 days earlier (June 1st), which coincides with nursery establishment dates for PTR.

1.2.3 Rice Varieties and Growth Duration

Based on phenological characteristics, rice varieties are classified into three broad categories. 'Short duration' varieties reach maturity within 110 days of sowing, 'medium duration' varieties mature in the range of 110–130 days, and 'long duration' varieties take 130 days and longer. The main varieties grown in the region are aromatic Basmati strains (e.g. PB-1509 or PB-1121) that generally fall in the medium to long duration category. High yielding improved inbred or hybrid strains (like PR-126, SAVA 7501 or SAVA 7301) are also available and tend to mature in 130 days or less. Varieties like PUSA 44, that take over 150 days to mature, are officially banned and not recommended because of their high water demand and low resistance to disease. Nevertheless, PUSA 44 seed is still available for purchase. All varieties takes on average 15 days longer to mature under PTR than DSR – likely due to transplanting shock (Lee et al. 2021) – and DSR typically reduces yield by 10–15% relative to PTR (personal communication; KVK Karnal, 2024). For improved inbred varieties like PB-126 yields around $7.4\,\mathrm{t\,ha^{-1}}$ can be expected. Basmati varieties like PB-1509 yield around $4\,\mathrm{t\,ha^{-1}}$ to $4.5\,\mathrm{t\,ha^{-1}}$, but have a considerably higher market value (PAU 2024).

1.2.4 Irrigation Scheduling

Flood irrigation persists as the predominant irrigation method for both rice and wheat in northwest India because of its operational simplicity and long-standing tradition. Despite decades of research experimenting with furrow, drip or subsurface irrigation the common practice has not changed significantly. In PTR systems, farmers typically monitor their fields multiple times a week and, applying irrigation when ponded water levels drop below locally determined thresholds - a practice driven mainly by experience. While Punjab Agricultural University (PAU) recommends maintaining 5 cm to 10 cm of standing water for the first two weeks post-transplanting followed by irrigation two days after complete infiltration (PAU 2024), actual practices frequently diverge due to unreliable electricity access and risk-averse farming strategies. Erenstein (2009) report that farmers irrigate rice 35 times on average, which shows that farmers likely maintain continuous flooding throughout the season. Requiring 6–8 times less water, wheat is only irrigated 3–4 times in a season.

Since water savings have become a concern in the region, the technique of alternate wetting and drying (AWD) in PTR has gained institutional support. This method employs perforated tubes to monitor water tables and irrigation is triggered when levels drop 15 cm below the surface; typically 3–4 days after water recedes. In DSR farmers are advised to apply a heavy initial flooding directly after sowing, followed by an irrigation after 4 days, and subsequent irrigations every 5–7 day throughout the rest of the season (PAU 2024). In terms of irrigation water savings, DSR and AWD have shown comparable results, demonstrating up to 30% water savings in trials (Husain et al. 2009; Ishfaq et al. 2020). Despite these benefits, adoption among farmers is limited. Additionally, the PAU has developed a hybrid system called tar-wattar DSR (combining puddling with delayed irrigation). While

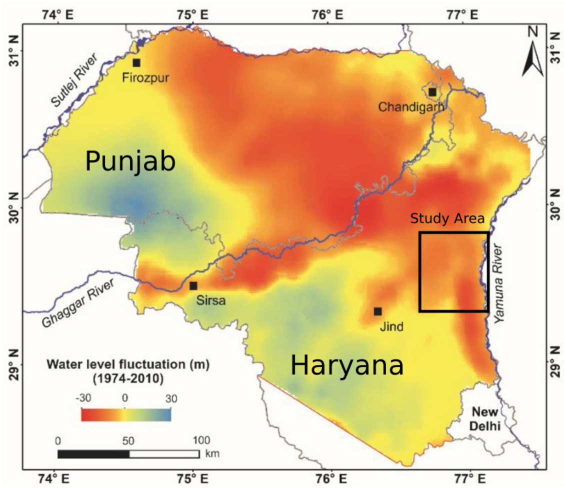

Figure 1.2: Long term (1974-2010) groundwater head fluctuation in Haryana and southern Punjab. Red indicates decrease, blue indicates increase. The black box marks the district of Karnal; the main focus of this thesis. Adapted from Kumar Joshi et al. (2021).

being an interesting development, this innovation has not yet penetrated Haryana's agricultural practices and thus falls beyond this study's scope.

In addition to AWD and DSR a host of other technical and managerial solutions have been proposed to decrease water requirements (Humphreys et al. 2010; Jovanovic et al. 2020; Perry et al. 2017; Ahmad et al. 2014). These include land preparation techniques like laser land leveling, irrigation methods like furrow or drip irrigation, and cultivation systems like raised bed cropping, and growing alternative crops with less water demand. All are purported to save water, while some also have other benefits like saving labor and time. Generally, these water-saving technologies (WSTs) either try to maximize supply-side recharge or minimize irrigation demand.

1.3 Problem Description

As alluded to above, the current intensive rice-wheat cropping system has led to severe groundwater depletion in much of Punjab and Haryana (R. Singh 2000; Rodell et al. 2009; MacDonald et al. 2016; Kumar Joshi et al. 2021). Piezometer data show an average annual decline of 0.49 meter ($\pm$0.43 m) between 2000 and 2010 (Kumar Joshi et al. 2021), with localized rates exceeding 2 m/year in some districts. This depletion is driven by unsustainable irrigation practices, where groundwater abstraction far exceeds natural recharge. This decline in the groundwater table is primarily leading to increased energy requirements and costs for pumping. It also increases cost for tube-well construction, and potentially deteriorating groundwater quality in the lower reaches of the aquifer (Bonsor et al. 2017) raises legitimate concerns as to the long-term viability of the current cropping system. All this poses a central threat to national food security and India's position as a leading global rice exporter (McDonald et al. 2022; Balwinder-Singh, McDonald, et al. 2019).

At the same time, strong economic incentives exist to maximize production and increase yield and productivity. While all stakeholders – including farmers, government agencies, researchers, and agribusinesses – recognize groundwater depletion as a problem, attempts to replace rice with less water-demanding crops have failed because of subsidies favoring rice, a flat-rate system for electricity used for irrigation, assured output markets and minimum support price guarantees (Balwinder-Singh, McDonald, et al. 2019). High overheads in the form of land rent (around 1500 USD/ha/year) further incentivizes tenant farmers to maximize production and profit so as not to lose money on their investment. More success has been achieved in compelling farmers to change agronomic practices within the rice-wheat rotation. The Preservation of Subsoil Water Act of 2009 for example is reported to have significantly reduced groundwater depletion (Tripathi et al. 2016) by forcing farmers to delay rice transplanting after June 10th.

Humphreys et al. (2010) establishe that water-saving technologies (WSTs) influence groundwater depletion through two primary mechanisms: enhancing recharge via deep percolation from the root zone or reducing evapotranspiration (ET); all else equal. While adaptations to irrigation scheduling like AWD can decrease gross irrigation applications by minimizing runoff and percolation losses, their regional-scale impact on groundwater depletion likely remains limited (Keller et al. 1996). This limited effect occurs because such "saved" water typically returns to the same aquifer system if it is reasonably shallow and phreatic. The added complexity of these return flows – often mischaracterized as inefficiencies – presents significant challenges for water accounting in groundwater irrigated systems, as they frequently contribute substantially to subsequent cropping cycles or downstream users within the basin.

Humphreys et al. (2010) argue that true groundwater conservation requires reducing ET, which can be achieved by growing crops during periods of lower evaporative demand (Balwinder-Singh, Humphreys, Gaydon, et al. 2015). Real progress has been made in this regard by delayed rice transplanting and timely sowing of wheat in northwest India. Short-duration (110-day) rice varieties can also significantly reduce ET (Balwinder-Singh, Humphreys, Sudhir-Yadav, et al. 2015), but these gains usually come with yield penalties due to the physiological coupling between ET, biomass production, and grain yields. These complexities make water accounting less straightforward than often laid out.

While WSTs like DSR and AWD are widely promoted by government and research institutions in northwest India, their actual impact on water conservation remains largely unclear. Specifically, there is often little distinction made between consumptive and non-consumptive use of irrigation water, and most evaluations focus narrowly on reductions in gross irrigation applications. This is problematic, as farmers often implement these technologies without clear evidence on whether they result in actual water savings, leading to inefficient water management and potential misinterpretations of policy effectiveness. This demonstrates that evaluating irrigation water savings requires a more nuanced analysis than commonly practiced, and proper accounting of water flows after field application is essential to avoid false con-

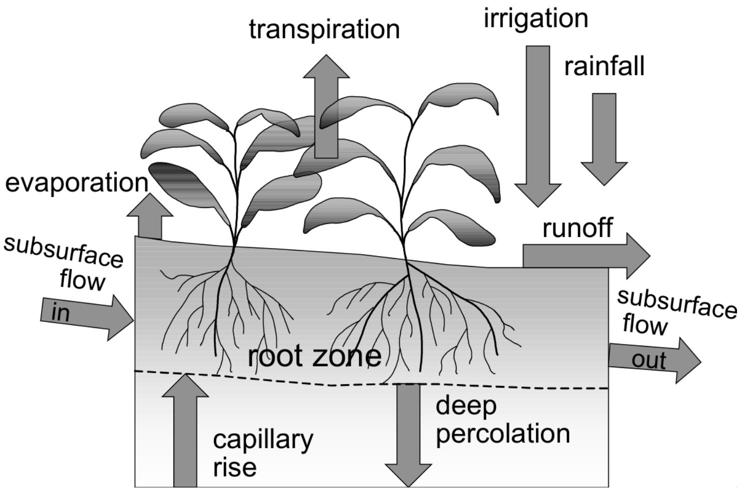

Figure 1.3: Soil water balance components of the root zone. Source: Allen et al. (1998)

clusions (Keller et al. 1996). Without the careful distinction between consumptive and non-consumptive water use, policymakers lack the evidence needed to identify which interventions truly conserve groundwater versus those that simply alter water distribution within the system.

1.4 Research Objective

Considering this situation, efforts were made in this thesis to systematically compare the three most common "package of practices" in northwest India in terms of their water withdrawal, consumptive ET and return flows, in order to assess the different cropping strategies' true potential for water saving, rather than only focusing on gross irrigation applications. The **cropping strategies under consideration** were:

(i) continuously flooded 'transplanted paddy rice' (PTR) followed by wheat,

(ii) water conserving irrigation scheduling in PTR (AWD) followed by wheat, and

(iii) direct seeded (DSR) rice followed by wheat.

Early, median and late crop establishment as well as short, medium, and long duration rice varieties were also compared.

A Python implementation of the FAO56 framework (Allen et al. 1998) was adapted and expanded to fit rice-specific needs, and each variation of the rice-wheat rotation was modeled for 30 years using weather data from 1989 to 2019. A short fallow after rice and a long fallow after wheat were also modeled. The thirty years average annual sums of evapotranspiration (ET), deep percolation and irrigation requirements for the entire crop rotation were then compared in terms of their potential effect on current groundwater depletion trends through a simple relationship between the aquifer's specific yield and observed groundwater head fluctuations.

This relatively simple methodology was chosen to demonstrate that a sound water balance assessment can be made with comparatively little effort and that a parsimonious modeling approach can yield results comparable to more complex models and field trials.[1] This thesis thus serves as a pragmatic starting point to understand how alternative cropping systems could mitigate groundwater decline in Haryana and how they might be adopted beyond the research setting, and provides a guideline for potential further more detailed investigations.

The **main research question** was posed as follows:

> *What are the individual and compound effects of rice establishment methods, (trans)planting dates, varietal duration, and irrigation scheduling on the annual plot-level water balance for a rice-wheat crop rotation in the district of Karnal, Haryana?*

For clarity, the main research question was further subdivided into:

1. How do the two establishment methods PTR and DSR differ in their respective irrigation requirements, evapotranspiration demand and deep percolation?
2. How does delaying seeding/transplanting dates affect irrigation requirements, evapotranspiration and deep percolation?
3. How do short, medium and long duration rice varieties affect irrigation requirements, evapotranspiration and deep percolation?
4. How does changing irrigation scheduling from continuous flooding to cycles of alternative wetting and drying affect irrigation requirements, evapotranspiration and deep percolation?

[1] The principle of parsimony in science reflects the notion that simple explanations of causes and effects with a minimal number of parameters or model components should be preferred over more complex approaches. Dubova et al. (2025) give an excellent account on the complexities of parsimonity and current advances in computer modeling.

Chapter 2

Research Framework

This study adopts a parsimonious research framework – a structured analytical approach that balances simplicity with explanatory power – to analyze water-saving interventions in rice-wheat systems. Grounded in the FAO56 methodology, the framework distinguishes between dry (non-consumptive) and wet (consumptive) water savings, in order to provide a precise assessment of how irrigation practices could affect aquifer depletion. The following sections detail the key hydrological and phenological concepts (evapotranspiration, deep percolation, and net abstraction), their mathematical formulations, and pareto optimization as a way to balance trade-offs between water conservation and yield.

2.1 Dry vs Wet Water Savings

When discussing water use and irrigation water savings, careful attention must be paid to how "savings" are defined, the scale of analysis, the sources of water, and where the water flows after application. To comprehensively assess these dynamics, Keller et al. (1996) proposes a basin-scale framework based on the ecological concepts of sources, sinks, and recycling. The main water *sources* in a basin include precipitation, surface stores (such as lakes, rivers, and canals), and aquifers. Water *sinks*, in contrast, are endpoints where water is not easily recoverable for direct use. Primary examples are soil evaporation and plant transpiration into the atmosphere, and drainage into the ocean, saline aquifers, or other locations where water becomes too polluted for reuse.

When water is withdrawn from a source and applied at a specific location within the basin, a portion is permanently lost to the atmosphere through evaporation and transpiration. The remainder drains into surface or subsurface storage (e.g. lakes or aquifers), where it may or may not be *recycled* for further use, depending on its quality (Seckler 1996). Because of this potential for water to be recycled on the basin scale, a further distinction should be made between *consumptive* and *non-consumptive* use (Perry 2007). Consumptive use of water occurs when water is lost to a sink, and non-consumptive use occurs when water can be recycled.

On field or plot level a slightly different set of concepts apply. As shown in Figure 1.3, the boundaries of a plot-level water balance analysis usually reach from the top of the plant canopy to the bottom of the root-zone. Everything that enters these boundaries is counted as an input, and everything that exits is counted as a loss. Rather than distinguishing between consumptive and non-consumptive use, water use is classified as beneficial and non-beneficial, and only crop transpiration and leaching requirements to manage root-zone salt concentrations are considered legitimate beneficial use. All other losses (evaporation, deep percolation, runoff) are considered a waste of resources (Keller et al. 1996).

Mathematically, the in and outflows of the soil water balance on a plot-level can be expressed as follows (Allen et al. 1998):

$$I + P = ET + DP + RO \pm \Delta SM \tag{1}$$

Where I is the irrigation water applied onto a plot, P is precipitation, ET is the evapotranspiration from the soil surface and plant cover, DP is deep percolation through the bottom boundary of the system, RO is runoff off the soil surface, and ΔSM is the change in soil moisture over the period the water balance is calculated.[1]

In discussions on water savings, the common approach has been to minimize non-beneficial losses, maximizing the ratio of water transpired to water applied. For example, consider a rice paddy irrigated with 1000 mm of groundwater, of which 500 mm is transpired by the crop, while the remaining 500 mm is lost through evaporation, deep percolation, and runoff. In this case, the irrigation application efficiency is 50 % (500 mm beneficial use / 1000 mm gross application). If water-saving technologies reduce gross irrigation to 700 mm while maintaining the same transpiration, the efficiency rises to 70 %, suggesting a 30 % gross water saving.

While this calculation is technically correct, it overlooks a crucial factor. The 'lost' water in the inefficient scenario may in fact return to the aquifer it was abstracted from and could be reused in subsequent seasons. It might also flow downstream, where subsequent users may in-fact be reliant on these 'inefficiencies'. From a basin-level perspective the case can be made, that the only true consumptive loss—water permanently removed from the system—is transpiration, which remains unchanged in both cases. Thus, no actual water savings occurred despite the apparent efficiency gain. This demonstrates that water savings and efficiency improvements must be interpreted with caution and with clear distinctions made between "dry" (i.e. apparent) and "wet" (i.e. real) savings (Seckler 1996). Equipped with this set of concepts, and by carefully accounting for consumptive water use via the soil water balance (Equation 1), the actual water-saving potential of the water-saving technologies discussed in the previous chapter can be properly assessed, and conclusive relationships between aquifer depletion and irrigation water use made.

[1]Fluxes from lateral sub-surface flows and capillary rise are not considered in this analysis.

2.2 Evapotranspiration

Evapotranspiration refers to the combination of two separate processes, where water is evaporated from a surface, and transpired by plants. Because of the difficulty of reliably distinguishing evaporation from transpiration in field trials, the two are generally lumped into one term. Apart from measuring evapotranspiration in trials using lysimeters or other equipment, one of the most widely used alternatives is to calculate evapotranspiration by making use of the standard reference evapotranspiration (ET_{ref}) and a crop coefficient. The methodology for this approach was first laid out by Allen et al. (1998) in the FAO Irrigation and Drainage Paper No. 56 (hereafter referred to as the FAO56 methodology) and subsequently refined in ASCE (2005).

To estimate crop water use and irrigation scheduling the reference evapotranspiration can be calculated as follows (ASCE 2005):

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where ET_{ref} ($\mathrm{mm\,d^{-1}}$ or $\mathrm{mm\,h^{-1}}$) is the reference crop evapotranspiration for a standard short reference crop of 0.12 m, R_n is the net radiation at the crop surface, u_2 is the mean daily wind speed at 2 m height, T is the mean air temperature, G is the soil heat flux density at the soil surface, e_s is the saturated vapor pressure, e_a is the actual vapor pressure, Δ is the slope of the saturation vapor pressure-temperature curve, and γ is the psychrometric constant.

ET_{ref} represents the influence of local climatic conditions on a hypothetical well-watered grass reference crop and is intended to provide a standard that allows for comparison of evapotranspiration at different times, locations and crops. The method uses the standard climatological records, solar radiation (or sunshine hours), air temperature, vapor pressure (or humidity) and wind speed in combination with latitude and elevation.

The crop evapotranspiration under standard conditions (ET_c) represents crop evapotranspiration under optimal growth conditions under the given climate with no water, disease, salt, nutrient or other stress is prevalent, and can be estimated using the following empirical relationship (Allen et al. 1998, forthgoing):

$$ET_c = (K_{cb} + K_e) \cdot ET_{ref} \tag{3}$$

where K_{cb} is the basal crop coefficient defined as the ratio of ET_c to ET_{ref} when the soil surface layer is dry but where the soil water content of the root zone is adequate to sustain full plant transpiration, and K_e is the soil water evaporation

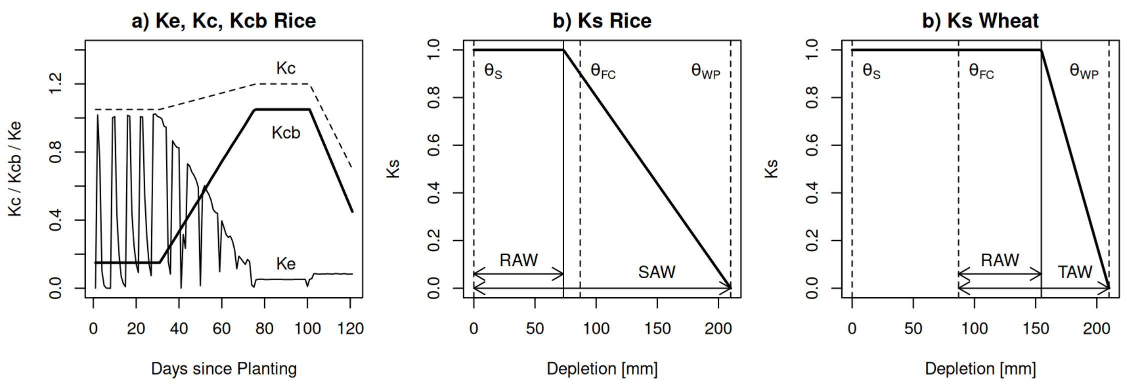

Figure 2.1: Crop coefficients and water stress relationships: (a) FAO56-derived crop coefficients (K_c, K_{cb}, and K_e) for rice across growth stages, showing the inverse relationship between basal (K_{cb}) and evaporation (K_e) coefficients, with K_c as their time-averaged sum; (b) and (c) Water stress coefficient (K_s) response curves for rice and wheat; with schematic relationship between saturation-available water (SAW), total available water (TAW), readily available water (RAW), and depletion fraction (p).

coefficient that describes the evaporation component from the soil surface. Together K_{cb} and K_e form the single crop coefficient K_c.

To simulate crop evapotranspiration under water stress conditions ET_c can be adjusted by a stress coefficient K_s, yielding actual crop evapotranspiration (ET_a):

$$ET_a = (K_{cb} \cdot K_s + K_e) \cdot ET_{ref} \tag{4}$$

where K_s describes the effect of water stress on crop transpiration, with $0 \leqslant K_s \leqslant 1$, and K_s is a function of soil parameters and crop physiology. In plant physiological terms, as soil desaturation increases it becomes harder for plants to extract water from the surrounding soil pores. After the root zone depletion exceeds a critical level, plants become water stressed, and transpiration gradually reduces to zero at the permanent wilting point (WP), corresponding to a K_s value of zero. K_s can be described as:

$$K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p) \cdot TAW} \tag{5}$$

where TAW is the total available water ($FC - WP$), RAW is the readily available water ($p \cdot TAW$), p is the depletion fraction and D_r is the depletion of residual soil moisture in the root zone. TAW, RAW, D_r and all other soil related parameters are functions of the soil's initial soil water content (θ_0) and the theoretical soil water content at field capacity (θ_{FC}) and wilting point (θ_{WP}).

Since the depletion fraction p of rice is measured from saturation, Equation 5 has to be adapted as follows:

$$K_{s,rice} = \frac{SAW - D_s}{SAW - RAW} \tag{6}$$

where SAW is the total available water at saturation ($SAT - WP$), and D_s is the depletion of soil moisture from saturation.

To illustrate the main variables in Equations 3 to 6, Figure 2.1 panel a) shows the FAO56 tabulated K_c values for rice in its different growth stages, as well as K_{cb} values and K_e values. As the crop grows K_{cb} increases and K_e decreases. While K_{cb}'s rate of change remains constant during the crop's growth according to FAO56, K_e fluctuates depending on irrigation timing and soil water availability. K_c can be interpreted as the time-averaged K_{cb} and K_e. Figure 2.1 panels b) and c) show stress coefficients K_s for rice and wheat as well as the relationship between SAW, TAW, RAW and p.

2.3 Deep Percolation

Most crops grow optimally under aerobic conditions where soils are fully drained and below field capacity. Due to the complexity of soil physics and unsaturated water flow and the assumption that irrigation managers will try to avoid excess irrigation, the FAO56 methodology simplifies the process of water flow through the root-zone by assuming immediate and perfect distribution upon application and total loss to deep percolation of all water above field capacity within 24 hours.

Unfortunately, this assumption does not hold for lowland rice varieties, which begin to show water stress just above field capacity (p = 0.2 of saturation; $\theta(p)$ = 0.29). To accurately model percolation rates in paddy rice (where fields remain continuously flooded) and in direct-seeded rice (DSR) (where farmers irrigate well before soil moisture reaches field capacity to minimize yield loss), soil hydraulic conductivity (K) must be introduced into the FAO56 methodology as a limiting factor to deep percolation.[2]

Unsaturated hydraulic conductivity in the vadose zone depends on a complex relationship between soil properties, water head pressure, initial volumetric soil moisture content, and time. Since the FAO56 method used here operates on a daily time-step, the van Genuchten approach (van Genuchten 1980) was selected for its relative simplicity over more complex models like the Richards equation, which requires finer time steps. K can be determined using the following closed-form equation:

[2]It is unfortunate that van Genuchten and FAO56 use a similar nomenclature. Please note that van Genuchten's K and K_{sat} refer to a soils (saturated) hydraulic conductivity and K_s, K_e, K_{cb}, and K_c refer to FAO56's crop, stress and evaporation coefficients. The two sets of nomenclatures, though similar, signify very different sets of concepts.

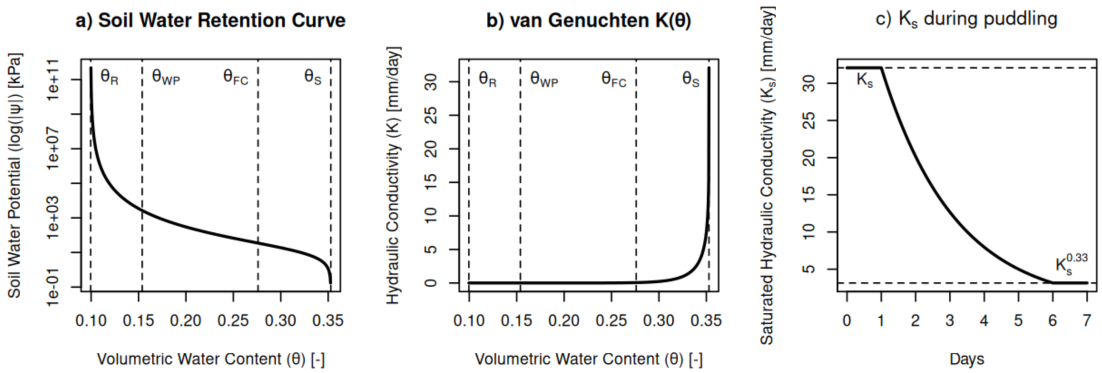

Figure 2.2: Soil water retention curve (a), hydraulic conductivity (b), and the saturated hydraulic conductivity (K_{sat}) (c) for a sandy clay loam soil (Kumar et al. 2019). The van Genuchten model is used to describe the highly non-linear relationship between volumetric water content (θ), matric potential head (ψ), and hydraulic conductivity (K). The empirical shape factors n, m, α and l of the water retention curve, were determined using the ROSETTA algorithm and soil texture and bulk density. K_{sat} was also determined using ROSETTA and is modified by puddling procedures described on Sections 1.2.1 and 2.3.1.

$$K(h) = K_{sat} S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{7}$$

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \tag{8}$$

where K_{sat} is the saturated hydraulic conductivity, S_e is the relative saturation; $\theta(h)$ is the volumetric water content at pressure h (expressed as matric potential head ψ [kPa]), θ_r is the residual water content (cm^{3}cm^{-3}), θ_s is the saturated water content (cm^{3}cm^{-3}), $m = 1 - 1/n$, and n and l are empirical shape factors of the water retention curve described by the Mualem (1976) pore-size model:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geqslant 0 \end{cases} \tag{9}$$

where in addition to the variables described above, α is another soil-specific empirical shape factor.

Visualized in Figure 2.2 panes a) and b) Equations 7 and 9 describe a soils water retention curve; i.e. the volume of water a soil can store in its pore space at any given pressure based on the pore-size model by Mualem (1976), and the corresponding hydraulic conductivity at this pressure. The determining soil parameters for this model can be determined experimentally (as for e.g. described by Li et al. 2014) or predicted from a soil probe's soil texture (% sand, silt and clay) and its bulk density using a pedotransfer function implemented in models such as RETC (van Genuchten et al. 1991) or ROSETTA (Schaap et al. 2001).

2.3.1 Land Preparation

Low-land paddy rice varieties grow best under anaerobic soil conditions, where a soil's water content is close to saturation. To achieve optimal growing conditions, farmers in northwest India employ intensive land preparation for puddled transplanted rice (PTR). The process begins with multiple harrowing passes to a depth of 25 cm, followed by cultivator tilling to break down residual stubble and loosen the soil. Farmers then apply heavy irrigation (∼250 mm) to saturate the field. Once saturation reaches ∼40 cm depth, an additional harrowing pass is performed under standing water to create a compacted hardpan layer, which reduces percolation losses. Finally, a leveling pass with a large plank is made to even out the field and guarantee uniform water distribution. Only after completing these steps is the field ready for rice transplanting.

To simulate the puddling effect on saturated hydraulic conductivity, the relationship between initial and puddled conditions was adopted from CROPWAT 8.0; the FAO's official FAO56 implementation (Smith 1996):

$$K_{sat,p} = K_{sat,i}^{0.33} \tag{10}$$

Where $K_{sat,i}$ is the initial saturated hydraulic conductivity ($\mathrm{m\,d^{-1}}$, and $K_{sat,p}$ is the final saturated hydraulic conductivity after puddling. Since land preparation typically occurs over multiple days, a daily decrease in $K_{sat}(t)$ can be calculated as follows (Smith 1996):

$$K_{sat}(t) = K_{sat,i} \cdot e^{\lambda \cdot \frac{t}{t_{tot}}} \tag{11}$$

$$\lambda = ln\left(\frac{K_{sat,i}^{0.33}}{K_{sat,i}}\right) \tag{12}$$

where $K_{sat,i}$ is the initial saturated hydraulic conductivity, t is the day to be calculated and t_{tot} is the total time for the land preparation, and $K_{sat,p} \leqslant K_{sat}(t) \leqslant K_{sat,i}$. For DSR and wheat, where seeds are either direct-sown into stubble or the field is prepared via conventional tillage (harrowing and laser land leveling without puddling), K_{sat} remains unchanged.

2.3.2 Net Abstraction

Furthermore, to link consumptive water use of crop production with aquifer depletion the following formula can be employed (Humphreys et al. 2010):

$$R - G = \mu \cdot \frac{\Delta h}{\Delta t} \tag{13}$$

where R is aquifer recharge (deep percolation) from irrigation and precipitation, G is groundwater abstraction, μ is the aquifers specific yield, and Δh is the head change over a specific time period t. $R - G$ represents the net abstraction from the aquifer and signifies the amount of water that is consumptively used for crop production. For a constant head level, net abstraction must be zero, and for simplicity, lateral groundwater fluxes in and out of the system are neglected.

2.4 Yield Response to Water Stress

Citing *FAO Irrigation and Drainage Paper No. 33* (Doorenbos et al. 1979), FAO56 describes the relationship between crop yield and evapotranspiration as:

$$1 - \frac{Y_a}{Y_m} = k_y \left(1 - \frac{ET_a}{ET_m}\right) \tag{14}$$

where Y_a and Y_m are the actual and maximal harvested yield, k_y is the crop specific yield response factor, and ET_a and ET_m are actual and maximum evapotranspiration. While this study does not quantify Y_a, Y_m, or k_y beyond very rough estimates, the equation confirms that yield reductions are directly proportional to reductions in evapotranspiration. For simplicity, this study therefore assumes that any decrease in evapotranspiration leads to some yield penalty.

This assumption warrants a strong caveat. Yield forecasting and dynamic crop water stress response is where the FAO56 methodology shows one of its key limitations. Designed primarily for irrigation planning and estimating gross irrigation requirements, FAO56 is a static water balance model. It does not simulate dynamic crop development (i.e. cumulative response of biomass and leaf area development to water stress) or phenological stress responses over time, nor does it account for non-linear interactions between daily growth and water availability. Instead, it assumes uniform crop growth with fixed-stage durations independent of water availability. Although stage-specific yield response factors exist, they were not applied here. As such, FAO56 offers only a first-order approximation of yield response to water stress, and should not be interpreted as a precise yield prediction tool.

Models like *AquaCrop* (FAO 2023) or *DSSAT* (Jones et al. 2003) address these shortcomings by simulating non-linear water stress effects and linking yield directly to cumulative transpiration and growing degree days rather than total evapotranspiration. Such tools are better suited for studies prioritizing yield prediction under variable water management. That said, FAO56 remains a pragmatic framework for this study's focus on comparing consumptive water use and water requirements across cropping strategies, as it requires less input data than more complex models.

2.5 Pareto Optimization

In the light of the previous sections, it should be clear that farmers in northwest India face a set of trade-offs. Minimizing water use will lead to yield reductions, while maximizing yield will lead to increased net abstraction, most likely from aquifers. Pareto optimization is a method to identify the most efficient trade-offs between two or more competing objectives. In this case, the objectives are to minimize net abstraction from the aquifer and to minimize reduction in evapotranspiration (ET) (and thus yield). A solution is considered Pareto optimal if no alternative exists that can simultaneously reduce net abstraction further without increasing ET reduction, or vice versa (Chang 2015).

Mathematically, for two solutions (a and b), solution b dominates solution a if:

(i) both components of b (net abstraction and yield reduction) are equal to or better than those of a, and

(ii) at least one of the components of b is strictly better than the corresponding component of a.

The set of all such non-dominated solutions forms the Pareto front, which represents the most efficient trade-offs available given the initial constraints. By plotting all possible combinations of establishment methods, irrigation practices, planting dates, and rice varieties in terms of their net abstraction and associated ET reduction, each combinations' performance in relation to the pareto front can be assessed. The analysis reveals which strategies provide the best balance between conserving water and maintaining yields.

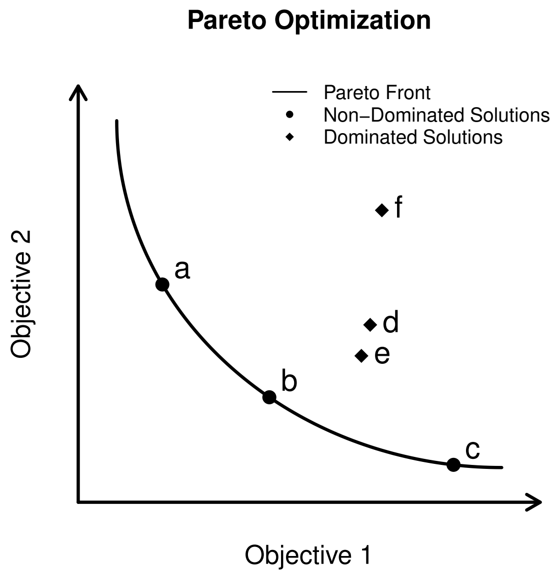

Figure 2.3: Schematic Pareto frontier showing optimal trade-offs between two competing objectives. Points a, b, and c represent non-dominated solutions, determine the position of the pareto front and are cosidered equal in terms of desirability. All other solutions (d, e, f) are sub-optimal dominated solutions that underperform in both objectives. The pareto front illustrates characteristic diminishing returns – improvements in one objective require increasingly larger sacrifices in the other.

Chapter 3

Methodology

This study implements an adapted version of the FAO56 water balance model using the open-source pyfao56 Python package, customized to improve model accuracy for hydrological dynamics and management particularities of rice-wheat systems in northwest India. While the framework presented in the previous chapter established the theoretical underpinnings of this study, the following sections detail the technical adaptations required to operationalize those principles.

3.1 FAO56 in Python

Since the publication of the FAO56 methodology in 1998, various software tools have been developed to implement its framework in computer code. One of the most widely used tools has been CROPWAT (Smith 1996), actively developed by the FAO until 2009. Due to limitations in the type of weather data CROPWAT 8.0 can handle, a more recent implementation called pyfao56 was used for this thesis.

Pyfao56 is an open-source software package written in the Python programming language (Thorp 2022) and is freely available on GitHub,[1] a code sharing platform. It is fully customisable and extendable and allows users to modify it to suit specific research needs. The package follows modern programming principles, and implements the FAO56 methodology through a modular structure based on Python *classes*. The package is designed to simulate a single realization of a crop system (e.g., a treatment or plot), and supports both the single and dual crop coefficient (K_c and K_{cb}) approaches. The model simulates a daily soil water balance over a growing season and outputs both daily values and seasonal summaries of the most relevant water balance components. Additionally, it includes visualization tools for plotting crop coefficients, irrigation schedules, and soil moisture dynamics.

In Python, *classes* provide the means to logically bundle *attributes* (parameters and variables) and *methods* (operations or functions). Attributes of a class are meant to store specific instances of data, and methods are defined to operate on and modify these data (van Rossum et al. 2009). For example, in pyfao56, an instance of the

[1] Source: `https://github.com/kthorp/pyfao56`

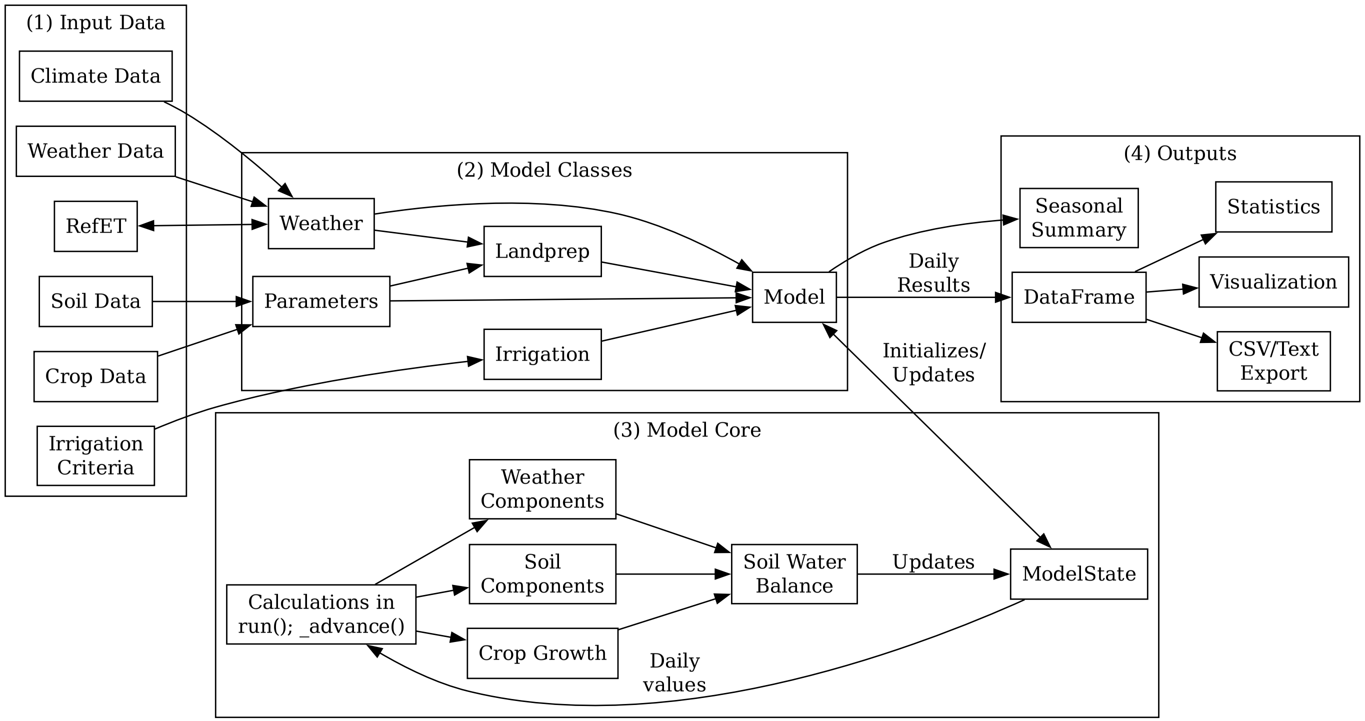

Figure 3.1: A visual representation of the structure and workflow of the adapted pyfao56 model in four components: (1) Input Data, where climate, weather, soil, crop, and irrigation criteria are supplied; (2) Model Classes, which organize input data into structured Python classes (Parameters, Weather, Irrigation, Landprep, and Model) as described on the following page; (3) Model Core, where daily calculations of the soil water balance are performed based on crop growth, daily weather data and soil parameters (see Figure 3.2 on ff. page); and (4) Outputs, which include daily results, seasonal summaries, visualizations, and options for further statistical analyses.

The Model Classes (2) supply the input data to the Model Core (3), where the primary water balance simulation occurs. The core simulation is driven by the `run()` method, which iteratively executes the `_advance()` function to progress through each day of the simulation. During each step, `_advance()` updates the ModelState, a data structure that tracks all daily variables (e.g. crop growth stage, ET_a, K_s, D_r, etc.). These variables are then used to compute the daily Soil Water Balance components (Rain, Irrig, E, T, ET_a, DP, RO, and ΔSM). The daily results of the ModelState are then stored in a DataFrame for further analysis, visualization, or export.

`Weather` class stores daily climate data as attributes and provides functionality as the method `compute_etref()` to calculate reference evapotranspiration (ET_{ref}) from its attributes. As available on GitHub, pyfao56 is structured into the following classes:

3.1.1 Parameters

The `Parameters` class stores all crop and soil related parameters required for the simulation. Users can input and adjust parameters such as crop coefficients (K_{cb}), rooting depth, depletion fractions, and growth stage durations. As methods, the class also allows loading and saving parameter values from and to files, allowing for the reuse of configurations across simulations.

3.1.2 Weather

The `Weather` class stores daily climate data, including solar radiation, air temperature, vapor pressure, wind speed, humidity, and rainfall. If not available, the daily reference evapotranspiration (ET_{ref}) can be calculated using the ASCE standardized method (ASCE 2005). As in the Parameters class, users can load and save weather data from and to files for external storage.

3.1.3 Irrigation

The `Irrigation` class stores irrigation data, including pre-defined irrigation events, depths, and application efficiency. The user can load and save irrigation event data from and to files, override irrigation events manually, and read irrigation data from the class. The use of this class is optional, and the model can be run without any irrigation at all, or with the `AutoIrrigate` class as an alternative.

The `AutoIrrigate` class gives the user fine-grained control over the models automatic irrigation scheduling, where irrigation is triggered when soil moisture depletion exceeds a specified threshold. It includes parameters to customize irrigation timing, amounts, and other constraints, such as the management allowed depletion, amount irrigated, precipitation forecasting, and days since last watering event. The class then computes irrigation events and depths based on the state of the models soil water balance for a specific date.

3.1.4 The Model

The core of the pyfao56 package, the `Model` class requires a start date, end date, fully populated instances of the `Parameters` and `Weather` classes and optionally, the `Irrigation` or `AutoIrrigate` class. The main method of the class then executes the FAO56 daily soil water balance model as described in Allen et al. (1998) Chapters 5 to 8 (see Figure 3.2 for a simplified schematization). After a model run the results can be saved to a file or printed directly to standard output (the console). Further optional settings in the model class are:

- Surface Runoff: The runoff calculation uses the USDA-NRCS (ASCE 2016) curve number (CN) approach, requiring an additional parameter (CN2) in the `Parameters` class.

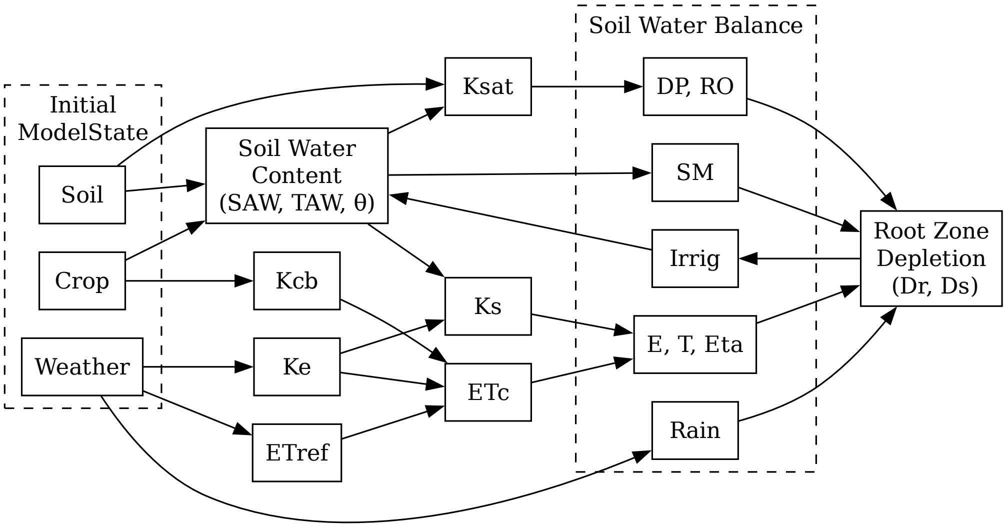

Figure 3.2: A visualization of the core components and calculation procedures within pyfao56's adapted `Model` class. The diagram is divided into three conceptual clusters: the Initial ModelState, the Soil Water Balance components, and the supporting calculations outlined in Chapter 2. The ModelState (dashed box, left) provides daily soil, crop, and weather data to the model. These inputs then determine the daily values of hydraulic conductivity (K), crop coefficients (K_{cb}, K_e), reference evapotranspiration (ET_{ref}), and soil water content (θ_i), which in turn determine the daily values of the water stress coefficient (K_s), crop evapotranspiration (ET_c), and saturated hydraulic conductivity (K_{sat}).

The Soil Water Balance components (dashed box, right) are then computed based on the daily values of the ModelState. Evaporation (E), transpiration (T) and actual evapotranspiration (ET_a) are calculated based on K_s and ET_c. Deep percolation (DP), runoff (RO) and residual soil moisture (SM) are calculated independently based on the θ_i, K_{sat} and paddy bund hight. Together with daily rainfall (Rain) the root zone depletion (D_r) is then updated. The model then determines the next day's irrigation requirements based on the current root zone depletion (D_r) and the irrigation parameters.

- Variable Depletion Fraction: Users can set the depletion fraction (p) to a constant value or varying with ET_c, as described in FAO56 Chapter 8, p. 163.
- Curvilinear K_s: Pyfao56 supports a curvilinear relationship between the stress coefficient (K_s) and root zone soil water depletion (D_r), as used in the AquaCrop model, in addition to the linear FAO56 relationship.
- Climate Adjusted $K_{c,max}$: The model can adjust tabular crop coefficients ($K_{c,mid}$, $K_{c,end}$, $K_{cb,mid}$, $K_{cb,end}$) based on local weather conditions, as described in FAO56 Equations 62, 65, and 70; Chapter 5; pp. 121 and following.

Pyfao56 includes further classes for retrieving weather forecasts, processing measured volumetric soil water content data and stratified soil layer information, computing statistics like root mean squared error and others, as well as visualization tools for plotting time series data and measured soil water data. These classes were not used in this study, and will therefore not be discussed in further detail.

3.2 Rice Specific Adaptations to pyfao56

As described in Section 2.3 there is no limit to daily deep percolation in the FAO56 methodology. To reasonably simulate irrigation requirements for current PTR and DSR practices, efforts were made to add a method for estimating the van Genuchten soil hydraulic conductivity (K) to the main `Model` class. This was done by adding saturated and residual soil water content θ_S and θ_R, and saturated hydraulic conductivity K_{sat} as attributes to the `Parameters` class, upon which daily average hydraulic conductivity K ($\mathrm{mm\,d^{-1}}$) is calculated as per Equation 7 in the Model Core. Daily deep percolation (DP) ($\mathrm{mm\,d^{-1}}$) is then calculated based on all drainable water in the root zone exceeding field capacity (FC) and below K ($0 \leqslant DP \leqslant K$; if $\theta_i \geqslant \theta_{FC}$). This assumes that the daily deep percolation will not exceed the daily average K determined by the van Genuchten method.

3.2.1 Land Preparation

An additional `Landprep` class was defined to calculate soil water balance components, Ks values and volumetric soil water content during puddling operations for paddy rice. This class constitutes a modified version of the `Model` class, relying on additional `Parameter` attributes. Like the `Model` class the `Landprep` class requires a start date, total number of days for land preparation, the number of days of puddling, the bund hight of the paddy, and fully populated instances of the `Parameters` and `Weather` classes. A soil water balance simulation is then initiated where the soil is saturated and the water table is brought up to a user defined level on the first day. Next, K_s and soil water content (θ_i) are calculated based on Equation 11. Irrigation is triggered whenever all water above ground has seeped into the paddy.[2] All subsequent calculations were taken from the original implementation of the `Model` class. The daily model results are stored in a DataFrame and as a summary, and $K_{sat,p}$, and θ_i are passed on to the `Parameters` class where they serve to initiate the subsequent `Model` run.

3.3 Model Parameterization

To understand local agronomic practices and gain a context for the broader agricultural system, six qualitative interviews with local farmers in Karnal and Panipat were conducted. These were complemented by four semi-structured interviews with agronomists from KVK Karnal and IRRI-ISARC to validate crop-specific parameters (rice varieties, growth durations, rooting depths, and stress thresholds), and gain insight into the specifics of irrigation scheduling and land preparation. Climate data was sourced from the Indian Meteorological Department (IMD) and the modeled WFDE5 dataset (Lange et al. 2021) for reference ET calculation. Where local crop specific parapeters were unavailable, data was sourced from FAO56 tables and peer-reviewed studies of northwest Indian cropping systems (specifically Kumar et al. (2019) for soil properties).

[2]This approach closely follows the rice-specific parameterization and land preparation adopted in CROPWAT 8.0.

3.3.1 Crop and Soil Data

The modified pyfao56 model was parameterized for the rice-wheat cropping system using the following crop and soil data:

Crop Stage Lengths: Data for rice and wheat were taken from the FAO56 Table 12. For rice the stage lengths were adjusted to totals of 100, 120 or 140 d based on ratios 0.25, 0.38, 0.21, and 0.17. These ratios were derived by dividing stage length over total crop length as described in FAO56.

Plant Height and Rooting Depth: Initial plant height for both rice and wheat was set to 5 cm with maximum height at 110 cm. Initial rooting depth was 0.2 m for both crops. Maximum rooting depths were 0.6 m for DSR, 0.5 m for PTR, and 1.2 m for wheat. Crop-specific values were collected through interviews with agronomists at KVK Karnal and IRRI-ISARC. Depletion fractions from FAO56 Table 22 were set to 0.2 (of saturation) for rice and 0.55 (of TAW) for wheat.

Soil Properties: Average soil texture and bulk density were taken from Kumar et al. (2019) and the van Genuchten parameters were derived using the ROSETTA algorithm.[3] One soil type (a sandy clay loam) for the whole root zone was assumed with the following values:

Parameter	θ_S	θ_{FC}	θ_{WP}	θ_R	K_{sat}
$cm^3\,cm^{-3}$	0.362	0.276	0.154	0.095	32.081

The depth of the surface evaporation layer (Z_e) was set to 0.1 m and REW was determined to be 6 mm (FAO56 Table 19; p. 144). Bund height was set to 0.3 m based on personal field observations in Karnal, and initial ponding depth was set to 50 mm.

Rice Planting Dates: Simulations were initiated on the 1st, 11th and 21st of each month from May 1st through July 21st. Each simulation included: (1) a 10 d fallow, (2) 125 d wheat crop, and (3) variable fallow periods (130 d, 110 d, or 90 d) completing the annual cycle. This structure captures full-year water balances from rice establishment.

Fallow Parameterization: For post-harvest bare soils, FAO56 recommends $K_{cb} = 0$ to simulate not plant transpiration. This allows the surface layer (top 10 cm) to dry to very low water contents, making K_e the sole reduction coefficient in Equation 4. Root depth parameters $Z_{r,ini}$ and $Z_{r,max}$ were set to 1 m to simulate the water balance of the top 1 m of the soil profile.

3.3.2 Irrigation Criteria

For PTR, irrigation was set to trigger when water level lowered below 10 mm and the paddy was refilled to a depth of 100 mm. The irrigation threshold in PTR was set based on the assumption that farmers irrigate whenever all water has dissipated into the paddy, and depth was calibrated to limit total number of irrigations to around

[3]Utilizing the online tool at: `https://www.handbook60.org/rosetta/`

10–12 which was determined from interviews with farmers in Karnal and Panipat. Irrigation treatments for DSR and AWD were set to trigger at −10 kPa, −20 kPa, −30 kPa, and −40 kPa soil matric potential head. This particular distribution was chosen based on the fact that a soils field capacity is defined at −33 kPa matric potential head and rice starts to experience water stress at −29 kPa for the given soil type (and p = 0.2).

In this way both frequent aggressive irrigation and more moderate infrequent irrigation was represented in the model. In reality farmers base their irrigation decision on other factors such as time since last irrigation event, or water level in a tube installed in the field. These decision criteria were not replicable in the model, so the matric potential was taken as the closest proxy. Number of irrigation events from the model runs were double-checked with experience values from farmers and staff at IRRI-ISARC to make sure that irrigation criteria were roughly calibrated. Each irrigation for AWD and DSR was set to refill the soil profile to saturation. Irrigation efficiency of all three methods was assumed to be 70 %.

3.3.3 Weather Data

Daily reference ET ('short' reference crop; Equation 2) was calculated by pyfao56's `RefET` module from 01/01/1989 to 31/12/2019, using the daily WFDE5 dataset from the ISIMIP repository (Lange et al. 2021) for location 9.707 98 °E, 76.954 14 °N (CSSRI Karnal Headquarters). The chosen location coincides with the test plot where soil samples were collected by Kumar et al. (2019). Observed daily rainfall was sourced from the Indian Meteorological Department (IMD 2024) for the same time period and location. Elevation was set to 253 m (ASL) (SRTM 2013) and wind speed measurement height was set to 2 m.

Table 3.1: Original pyfao56 model parameters.

Parameter	Description	Source	Unit
Crop Coefficient (K_{cb})	Initial, Mid, End	FAO56; Table 17	–
Stage Length (L)	Initial, Dev, Mid, End	FAO56; Table 11	days
Plant Height (h)	Initial, Max	KVK Karnal	m
Soil Water Content (TAW, θ_i, D_r)	Based on θ_{FC}, θ_{WP}	Kumar et al. 2019	mm
Rooting Depth (Z_r)	Initial, Max	KVK Karnal	m
Depletion Fraction (p)	% of TAW or SAW	FAO56; Table 22	–
Surface Evaporation Layer (Z_e)	Max Depth	FAO56; Table 19	mm
Stage 1 Evaporation (REW)	Total Depth	FAO56; Table 19	mm

Table 3.2: Additional parameters used for rice paddy simulation in pyfao56.

Parameter	Description	Source	Unit
Soil Water Content (SAW, θ_S, θ_R, D_s)	Residual, Saturated	Kumar et al. 2019	cm^3cm^{-3}
Saturated Hydraulic Conductivity (K_{sat})	Based on θ_S, θ_R	Kumar et al. 2019	$mm\,d^{-1}$
Paddy Bund Height (h_b)	Height of bunds	field observations	mm
Initial Water Ponding Depth (h_p)	Height of water in paddy	field observations	mm

Table 3.3: Weather parameters and sources employed for pyfao56 simulations.

Parameter	Source	Unit
Reference Crop Type	ASCE 2005	S/T
Weather Station Elevation	SRTM 2013	m
Weather Station Latitude	Kumar et al. 2019	°
Wind Speed Measurement Height	ASCE 2005	m
Year and Julian Day of Year	–	yyyy-ddd
Incoming Solar Radiation	WFDE5 2021	$MJ\,m^{-2}$
Daily Maximum/Minimum Air Temperature	WFDE5 2021	°C
Daily Average Vapor Pressure	WFDE5 2021	kPa
Daily Average Dew Point Temperature	WFDE5 2021	°C
Daily Maximum/Minimum Relative Humidity	WFDE5 2021	%
Daily Average Wind Speed	WFDE5 2021	$m\,s^{-1}$
Daily Precipitation	IMD 2024	mm
Daily Reference ET	Derived	mm

Chapter 4

Results

4.1 Current Cropping Practices in Haryana

From a survey of 80 farmers in the districts of Karnal, Panipat and Sonipat, Haryana (unpublished data; IRRI-ISARC 2024), the distribution of planting dates, harvest dates and season duration for various rice varieties was established (as shown in Figure 4.1). Despite considerable variability within and between varieties, three broad categories for seasonal duration were derived in accordance with local terminology. Sort-duration varieties were classified as < 110 days seed-to-harvest, medium duration varieties as 110 to 130 days and long duration varieties as > 130 days seed-to-harvest.

The shortest growing duration recorded was 98 days and the longest 164 days. Average season length was 125 days for direct-seeded varieties (DSR) and 137 days for transplanted varieties (PTR and AWD),[1] with the same varieties taking on average 15 days longer to mature when transplanted. Average planting in DSR and nursery establishment in PTR was June 1st ($\pm$13 days), and harvest dates were October 5th and 16th for DSR and PTR respectively ($\pm$19 days). All farmers had harvested their fields by November 14th.

Based on this data, and the irrigation practices outlined in Section 4.1 the following three rice cropping scenarios were defined and modeled in pyfao56 (hereafter referred to as current practices):

- **PRT:** puddled and transplanted June 20th; 140 days seed-to-harvest; irrigated to 10 mm upon subsidence of water below the soil surface.
- **AWD:** puddled and transplanted June 20th; 140 days seed-to-harvest; irrigated to saturation upon root zone depletion below -20 kPa matric potential head.

[1]For PTR and AWD farmers commonly count season duration from the day of transplanting, so in order to represent true phenological growing duration, an additional 25 days were added to the reported duration (PAU 2024).

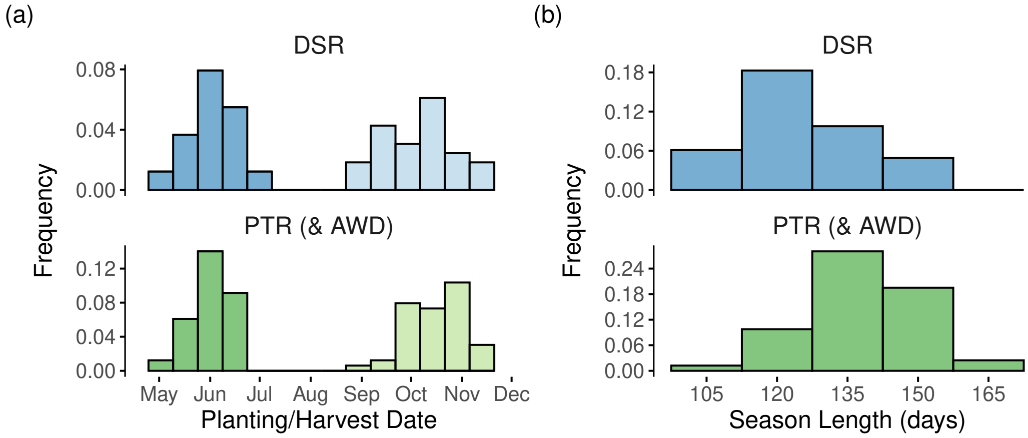

Figure 4.1: Rice crop calendar in northwest India (2024). (a) Distribution of planting dates for DSR and transplanting dates for PTR, with PTR dates adjusted by +25 days to account for nursery duration. (b) Variability of growing season duration (seed-to-harvest). Note: Alternate wetting and drying (AWD) was not assessed in the survey, and PTR durations are recorded from transplanting date. Source: Unpublished survey data (IRRI-ISARC 2024).

- **DSR:** non-puddled; direct-seeded June 1st; 120 days seed-to-harvest, irrigated to saturation upon root zone depletion below −20 kPa matric potential head.

In addition to the three rice crops, a short fallow of 10 days, followed by a standard wheat crop (using standard data from FAO56 Tables 11, 17, and 22) and a long fallow of 110 days (PTR and AWD) or 90 days (DSR), were modeled to simulate a full annual water balance. The simulations were started from rice planting or transplanting with an initial soil moisture depletion of 50 %. The nursery stage of PTR and AWD were not modeled in this study.

4.2 Current Water Requirements

4.2.1 Irrigation Requirements

In terms of irrigation requirements, the modeled AWD rotation emerged as the most effective water-saving technology, requiring only 620 mm of gross irrigation for the rice crop – a 30 % reduction compared to PTR (900 mm). The rice crop in the DSR rotation showed a 15 % reduction in irrigation requirements (762 mm) compared to PTR. The reason why AWD performed better in terms or irrigation requirements was because DSR showed substantially higher percolation rates, due to the lack of a puddled layer.

When considering the entire rice-wheat rotation, the water-saving potential of DSR diminished slightly. Due to lower residual soil moisture upon harvest and an earlier harvest, the subsequent wheat crop required additional irrigation of around 30mm, reducing the rotation's annual irrigation savings to 10 % compared to PTR.

Similarly, the AWD-wheat rotation's annual irrigation savings decreased to 25 % when accounting for the fallow periods and wheat crop. This shows that irrigation contribution to the follow-up crop in rice is non-negligible, and that continuous flooding has a favorable effect on irrigation requirements in wheat.

4.2.2 Actual Evapotranspiration

Annual ET_a (i.e. consumptive water use) showed minimal variation across the three current practices. The DSR rotation showed the lowest total ET_a (948 mm), followed by AWD at 987 mm, and PTR at 995 mm. The 5 % difference between DSR and TPR is likely due to DSR's shorter growing duration (120 days vs. 140 days) and the lack of a water-intensive land preparation phase (∼50 mm additional evaporation over 10 days). In all three cases, the rice crop accounted for around 65 % of consumptive water use. The slight variations recorded for the wheat and fallow seasons seen in Tables 4.1 to 4.3 likely reflect modeling artifacts.

4.2.3 Evaporation and Transpiration

Total evaporation accounted for around 36 % of ET_a in the DSR rotation, and 42 % in the AWD and PTR rotations, while transpiration represented the remaining 64 % and 58 %, respectively. For the rice crops specifically, the transpiration was 50 % to 53 % of total ET_a. No significant difference in variation between irrigation treatments was observed. This shows that regardless of establishment method and irrigation scheduling, the rice crop drives consumptive water use and evaporation remains high even in DSR. This reflects the fact that frequent irrigation is necessary in all scenarios to keep the soil above field capacity, which in turn means that the soil retains its full evaporative potential, even without standing water in the paddy.

4.2.4 Deep Percolation

Deep percolation was only slightly lower in DSR than PTR (412 vs 450 mm). This minimal difference can be attributed to the large difference in saturated hydraulic conductivity due to the absence of a puddle layer in DSR. This led to frequent irrigation with high percolation losses in DSR, where irrigation was applied every 2 to 4 days to keep root zone soil moisture above field capacity during the initial and development stages. Heavy rainfall events (> 100 mm) further exacerbated percolation losses, with percolation rates of up to $32\,\mathrm{mm\,d^{-1}}$ occurring multiple times per season. In contrast, PTR's puddled layer maintained a constant percolation rate of $3.5\,\mathrm{mm\,d^{-1}}$, even during heavy rainfall. This shows that a well-established puddle is especially important for retaining rainwater.

In contrast to DSR, deep percolation was significantly lower in the AWD scenario, with a reduction of 56 % compared to PTR (198 mm; 252 vs 450 mm). Although both methods involve puddling ($_{sat}$ = 3.5 mm), their irrigation scheduling differs significantly. Rather than being continuously flooded, AWD was only irrigated to saturation, which limited deep percolation to periods following large rainfall events when standing water persisted for multiple days in the paddy. Generally, percolation rates returned to near zero within 2 to 3 days after an irrigation event.

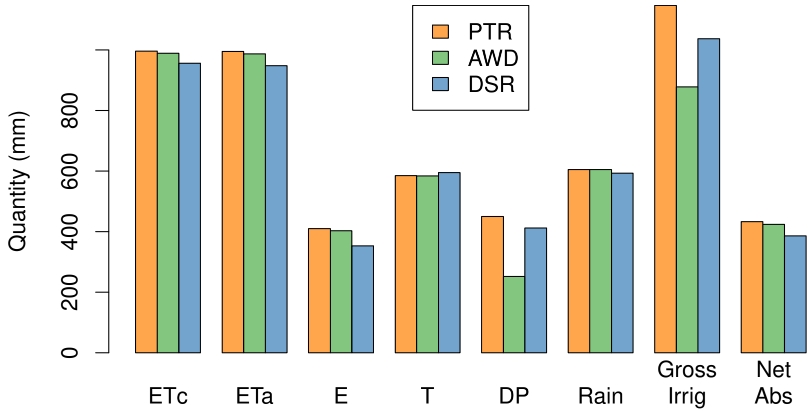

Figure 4.2: Modeled soil water balance components for DSR-Wheat, PTR-Wheat, and AWD-Wheat rotations in Karnal, Haryana. Data represent annual totals of 30-year mean values from Tables 4.1–4.3, with initial soil moisture at 50% depletion.

Wheat contributed very little to deep percolation (∼10 mm over the whole season), as it required only a total of three to four irrigation events per season, and rainfall during this period was minimal (50 mm). Similarly, the long fallow period showed negligible percolation, with the 50 mm of rainfall primarily replenishing soil moisture depleted by the wheat crop.

4.2.5 Net annual abstraction

As the difference between deep percolation and net irrigation, net abstraction represents the depletion of groundwater resources. Assuming that all irrigation is from groundwater, and no other sources of aquifer recharge exist beside the captured deep percolation, Equation 13 states that any volume of water abstracted leads to a direct decrease of the groundwater table proportionate to the specific yield of the aquifer. Applying this method, the DSR rotation performed best out of the three current strategies. It resulted in an annual net abstraction of 386 mm, 47 mm lower than PTR (433 mm), and 38 mm lower than AWD (424 mm). While this shows that DSR had the lowest impact on groundwater depletion, in absolute terms the differences were modest. Relatively, DSR achieved a 9 % reduction in net abstraction compared to PTR, while AWD only achieved a 2 % reduction.

This shows, that for all three rice-wheat rotations, annual net abstraction remains too high to stop groundwater depletion, and irrigation requirements and annual recharge do not match. Additionally, the distinct difference between reduced irrigation requirements (269 mm) and reduced net abstraction (9 mm) in AWD vs PTR shows how important a clear differentiation between wet and dry water savings in water accounting can be. Reducing deep percolation does in-fact not lead to decreased groundwater draw-down in this case, because all irrigation water "lost" to deep percolation returns to the aquifer and does not constitute a consumptive use. To decrease net abstraction, water saving strategies should therefore focus on reducing ET_a, which is irrevocably lost to the atmosphere. Additionally, the interaction between rice, wheat, and fallow periods further complicates the situation. For ex-

Table 4.1: Water balance for **PTR-Wheat** rotation. Values represent 30-year averages under continuous flooding (10 cm ponding depth) with 120 day field duration (transplanted June 21 after 20 day nursery period). Total season length: 140 days seed-to-harvest.

Crop Type	Dur ation (days)	Estab Date (d/m)	ET_c (mm)	ET_a (mm)	E (mm)	T (mm)	DP (mm)	Rain (mm)	Gross Irrig (mm)	Net Abs (mm)
Rice	140	21/06	667	667	335	332	421	474	900	271
Fallow	10	19/10	14	14	14	0	10	2	0	-10
Wheat	125	29/10	271	271	18	253	11	55	247	179
Fallow	110	03/03	44	44	44	0	7	74	0	-7
Total	140	21/06	996	995	410	585	450	605	1147	433

Table 4.2: Water balance for **AWD-Wheat** rotation. Values represent 30-year averages under −20 kPa irrigation threshold with 120 day field duration (transplanted June 21 after 20 day nursery period). Total season length: 140 days seed-to-harvest.

Crop Type	Dur ation (days)	Estab Date (d/m)	ET_c (mm)	ET_a (mm)	E (mm)	T (mm)	DP (mm)	Rain (mm)	Gross Irrig (mm)	Net Abs (mm)
Rice	140	21/06	666	664	333	330	228	474	620	249
Fallow	10	19/10	6	6	6	0	7	2	0	-7
Wheat	125	29/10	273	273	20	253	10	55	257	188
Fallow	110	03/03	44	44	44	0	7	74	0	-7
Total	140	21/06	989	987	403	584	252	605	878	424

Table 4.3: Water balance for **DSR-Wheat** rotation. Values represent 30-year averages under −20 kPa irrigation threshold with median planting on June 1 and 120 day variety duration seed-to-harvest.

Crop Type	Dur ation (days)	Estab Date (d/m)	ET_c (mm)	ET_a (mm)	E (mm)	T (mm)	DP (mm)	Rain (mm)	Gross Irrig (mm)	Net Abs (mm)
Rice	120	01/06	632	624	293	331	383	484	762	203
Fallow	10	29/09	4	4	4	0	16	6	0	-16
Wheat	125	09/10	282	282	17	265	13	49	276	199
Fallow	110	11/02	39	39	39	0	0	54	0	0
Total	120	01/06	956	948	353	595	412	593	1037	386

ample, the slightly higher net abstraction for the wheat crop in the DSR scenario, due to the higher soil moisture depletion after DSR harvest, diminished the water saving potential of DSR. This highlights the importance of taking an integrated approach to water budgeting where follow-up crops are accounted for in the annual water balance assessment.

4.3 Observed Local Depletion Trends

To stabilize the groundwater table, an ET_a reduction target has to be established. For this purpose, a linear regression of piezometer head data from 2010 to 2020 from three wells surrounding the modeled test site (unpublished data; IRRI-ISARC 2024) was carried out. The results indicate an average decline of 0.75 m/yr. Assuming an aquifer specific yield of 10 % to 15 % (Humphreys et al. 2010), this decline corresponds to an annual net abstraction of approximately 75 mm to 113 mm, which in turn corresponds to an ET_a reduction target of ∼100 mm to reduce net abstraction to near zero.

In contrast to this data, the pyfao56 model estimated an average annual net abstraction of 386 mm to 433 mm for the current cropping scenarios AWD, PTR and DSR. These values clearly overestimate actual net abstraction.[2] Assuming the modeled annual net abstraction of ∼400 mm is correct, this means that there must be other substantial sources of recharge not accounted for in this analysis. With the given actually observed net abstraction of ∼100 mm, this would amount to an additional 300 mm of recharge, with the model currently only capturing 25 % of the overall recharge.

This discrepancy between model and reality can be attributed the choices made during the model setup. The model assumes a closed system, where all irrigation water comes from groundwater and all recharge occurs on the plot. In reality, irrigation is likely to be a mix of canal water and groundwater, and other sources of recharge across the landscape (streams, canal inefficiencies, rainfall) likely also substantially contribute to broader recharge. In this specific case, lateral groundwater flow from nearby rivers would also have to be factored into a proper groundwater flow analysis. Piezometer head data, close to the Yamuna river (situated around 30 km east of Karnal) for example, show much lower depletion trends of 0 to 20 cm/yr over the period 2010 to 2020. The model also focuses solely on agricultural water use, while actual groundwater depletion is influenced by additional factors such as domestic and industrial abstraction.

Despite these caveats, the model's results remain useful for understanding the relative impact of different cropping practices on groundwater depletion. Based on the observed data the conclusion can be made that reductions of ∼100 mm in net abstraction (roughly 10 % of ET) are required to mitigate the observed recharge deficit, and the model data, specifically the ET_a values, can be used to estimate

[2] Interestingly, Jalota et al. (2002) overestimate net abstraction by a similar degree using another soil water balance model and pan evaporation as reference ET.

the potential of different management strategies to achieve this target. The reduction targets presented here are roughly in line with previous observations made by Humphreys et al. (2010). For Gujjarwal in the Punjab they estimate an average reduction target of 150 mm at a specific yield of 15% and an annual draw-down of ∼1 m.

4.4 Optimized Water Savings

4.4.1 Correlating ET_a and Net Abstraction

To determine if and how the 100 mm ET reduction target could be met, all combinations ($n = 189$) of planting dates (May 21st to July 21st), varietal duration (100, 120, 140 days), and irrigation criteria (10 mm for PTR; −10, −20, −30 and −40 kPa for DSR and AWD) were modeled using the modified pyfao56 python package. To identify their relative effect on ET_a and net abstraction, a multiple regression analysis was conducted, which showed a clear correlation of 1.01 for all three methods ($R^2 = 0.97$, $p < 0.001$). This suggests that, assuming causality, every millimeter of water evapotranspired depletes groundwater by approximately 1 mm above the threshold of 541 mm ET_a; the intercept of the linear regression. This threshold corresponds to the average annual precipitation minus ∼60 mm surface evaporation.

This correlation between ET_a and net abstraction confirms, that in order to stabilize groundwater decline (i.e. zero net abstraction), annual ET_a must be brought in line with annual net recharge. When not accounting for additional recharge this amounts to a required reduction of around 350 mm to 400 mm ET_a (or ∼40 % of current ET_a); and when accounting for *actual* groundwater draw-down this is 75 mm to 113 mm, or ∼10 % current ET_a.

4.4.2 Delaying Planting Dates

The analysis further revealed that delaying planting dates was the most effective strategy for lowering ET_a and net abstraction. Specifically, every 10 day delay in planting until June 21st reduced ET_a by 50 mm from over 500 mm in May to around 350 mm on June 21st. This can be attributed to the considerable decrease of the reference ET (itself a function of temperature and solar irradiation, among others) with the onset of the monsoon in late June. Further delaying planting dates until July 21st resulted in an increased net abstraction of 15 mm per decade, suggesting the ideal planting date to be around the last week of June.

4.4.3 Varietal Duration and Irrigation Scheduling

The second most effective strategy for reducing ET_a was shortening the varietal duration by 20 days (from 140 days to 120 days to 100 days), which decreased ET_a by approximately 70 mm per 20 day period. This reduction occurs because a shorter growing season limits total crop transpiration, thereby lowering overall irrigation demand.

In contrast, irrigation scheduling showed a more varied effect on ET_a. Compared to the −10 kPa threshold, the −30 kPa and −40 kPa irrigation thresholds reduced

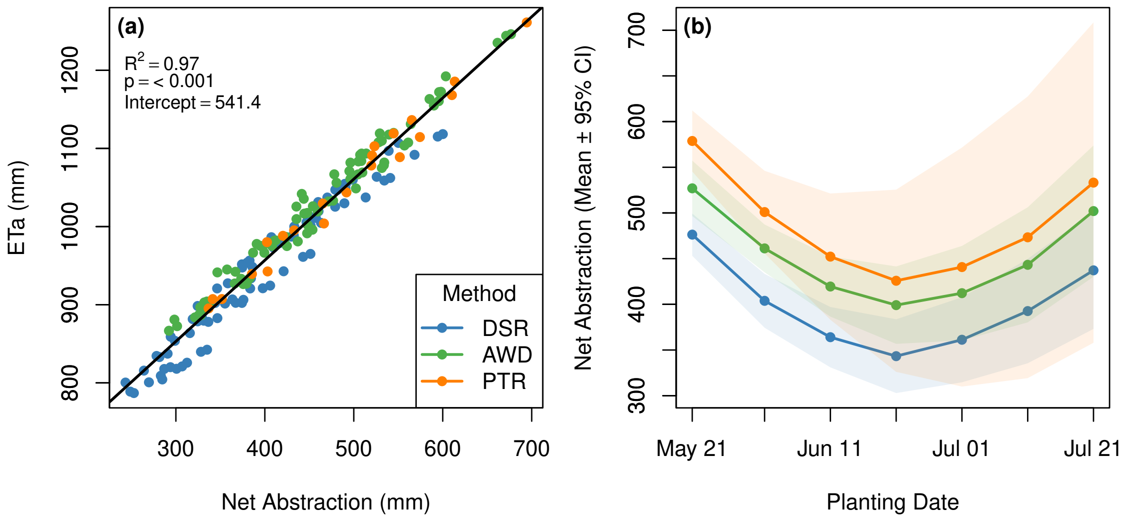

Figure 4.3: Water balance relationships from a multiple regression analysis. (a) Linear regression of actual evapotranspiration (ETa) versus net abstraction (n = 189 scenarios) showing an almost one-on-one correlation (R^2 = 0.97) for all three strategies. (b) Net abstraction by DSR planting date and AWD/TPR nursery estblishment (mean ±95% CI). The wider confidence intervals for PTR (1 irrigation criteria; n = 12 scenarios) reflect a higher uncertainty in mean estimates because of fewer variations compared to DSR and AWD (4 irrigation criteria; n = 48 each). Delayed planting consistently reduces net abstraction across all methods.

ET_a by 35 mm and 85 mm, respectively. No significant differences were observed among the 10 mm, −10 kPa, and −20 kPa treatments. The likely reason for this is, that for scheduling thresholds above −30 kPa (and thus above field capacity), the crop does not experience any water stress and soil evaporation remains largely unaffected, as frequent irrigation every 2 to 4 days was necessary to maintain the target rootzone soil moisture in the early stages of crop growth. This prevented the soil from sufficiently drying to cause any reduction in evaporation. This indicates, that while irrigation scheduling can contribute to water savings, its impact is less pronounced than that of agronomic modifications such as adjusting planting dates or varietal duration.

4.4.4 ET and Yield Response

The causal relationship between ET_a and yield is well documented in agronomic theory (Doorenbos et al. 1979; Steduto et al. 2012, aka FAO Irrigation and Drainage Papers No 33 and 66), where crop transpiration directly drives biomass production and yield. This means, that while reducing overall crop evapotranspiration (ET_c) can lower net abstraction, it typically results in a yield penalty. This trade-off arises because shortening the varietal duration reduces cumulative transpiration, leaving less time for the crop to develop fully. However, this yield reduction can be partially mitigated through targeted breeding. While high-yielding, short-duration varieties (e.g., PR-126 rice) demonstrate that careful varietal selection can maintain produc-

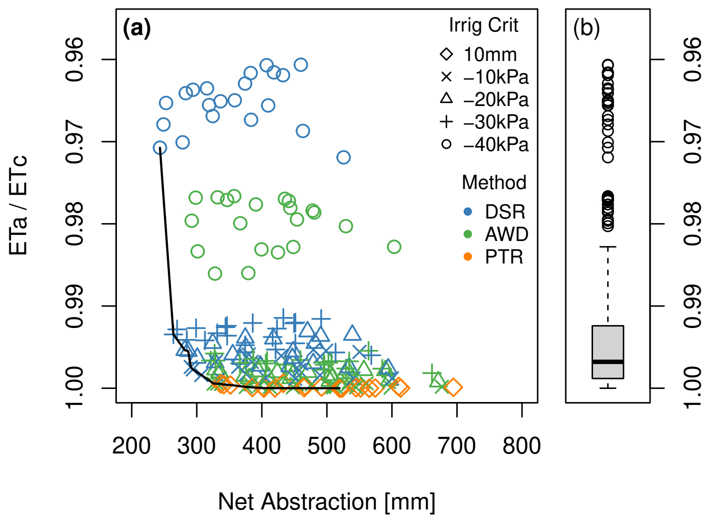

Figure 4.4: Pareto analysis of water saving strategies ($n = 189$ scenarios): (a) Trade-offs between net groundwater abstraction and ET reduction (ET_a/ET_c) showing method-specific outcomes and irrigation criteria (shape-coded). The Pareto frontier (black line) identifies optimal solutions. (b) Distribution of ET reduction ratios showing all scenarios maintain >95% ET_a/ET_c (95% quantile = 0.963), with median ET reduction of 0.997 (IQR: 0.992–0.999).

tivity while reducing ET_c and water demands, the fundamental constraint remains. For a given variety, ET_c reduction under optimal conditions inherently constrains yield potential.

Following from the same principles, reducing ET_a compared to ET_c through inducing water stress also incurs yield penalties in most cases. FAO56 approximates the yield reduction by the linear yield-response coefficient k_y (Equation 14).[3] Evaluating the effect of irrigation scheduling on ET reduction, the different irrigation treatments showed no significant variation above the −30 kPa irrigation threshold (average reduction: 3±2 mm; < 1 % of total ET_c). This reflects the physiological characteristics of the lowland rice varieties modeled, which start to exhibit water stress at −29 kPa, just above field capacity. The −40 kPa threshold on the other hand, produced an ET reduction of around 30 mm (2 to 4% of ET_c). Further model simulations using PAU-recommended fixed scheduling every 5-7 days, showed a ET reduction of ∼5 %. This is roughly in line with reported data collected from local farmers, and shows that for all irrigation scheduling above field capacity, ET reduction is near zero and variation can be considered non-significant.

[3]Sophisticated parameterizations for non-linear yield responses to reduced growing periods and water stress are lacking in the FAO56 framework, meaning only cursory observations could be made in the scope of this study.

Table 4.4: Annual water balance components for Pareto optimal cropping strategies (first three rows), and suboptimal strategies employing −40 kPa irrigation scheduling (last two rows). All scenarios are based on the 100 day varietal duration (+20 day nursery for TPR and AWD) and planting date of June 21st.

Method	Dur ation (days)	Plan ting (d/m)	Trans plt. (d/m)	Irrig Crit	ET_c (mm)	ET_a (mm)	DP (mm)	Rain (mm)	Irrig (mm)	Net Abs (mm)	ET Red. %
PTR	120	21/06	11/07	10 mm	896	895	416	627	979	337	< 1
AWD	120	21/06	11/07	−30 kPa	888	887	268	627	772	326	< 1
DSR	100	21/06	na	−30 kPa	837	833	405	595	892	282	< 1
AWD (DI)	120	21/06	11/07	−40 kPa	885	867	242	627	450	292	2.0
DSR (DI)	100	21/06	na	−40 kPa	824	800	236	595	534	243	2.9

4.4.5 Pareto Optimization

Based on the model results, pareto optimal solutions were identified that simultaneously: 1) maximize groundwater conservation through reduced net abstraction, and 2) minimize yield penalties by maintaining an adequate ET_a/ET_c ratio. These can be seen in Table 4.4.

The optimal scenarios for all three methods resulted in reduced net abstraction by around 100mm, compared to current practices. In PTR net abstraction was reduced from 433 mm to 337 mm, in AWD net abstraction was reduced from 424mm to 326mm, and in DSR net abstraction was reduced from 386 mm to 282 mm. In terms of ET_a, PTR was reduced from 995mm to 896mm (10% red), AWD was reduced from 987mm to 887mm (10% red), and DSR was reduced from 948 to 833mm (12% red). These savings were achieved by delaying planting and transplanting dates by 20 days and reducing varietal duration by 20 days (from 120 to 100 days in DSR and 140 to 120 days in PTR and AWD). The irrigation scheduling was also optimized for DSR and AWD, with the −30 kPa threshold emerging as the optimal solution. Table 4.4 also shows the results for AWD and DSR under the −40 kPa irrigation scheme. While this resulted in a further reduction of 20 mm to 30 mm in ET_a, it also led to direct proportionate increase in ET reduction of 2 to 3%.

These results mark a crucial point. Reducing net abstraction does not primarily hinge on irrigation method, but the choice of transplanting and sowing dates and crop variety. Delayed planting leads to reduction in ET_a due to less evaporative climate, and a shorter-duration variety leads to less ET_a due to a reduction of days the crop is growing in the field, and thus transpiring. Optimized practices in terms of delaying planting dates and choosing short-duration rice varieties can reduce net abstraction from over 500 mm to around 300 mm without significant ET reduction (and yield loss) *regardless* of establishment method or irrigation scheduling. Further reductions in net abstraction require accepting potentially substantial productivity penalties because plants no longer transpire at their maximal potential.

Chapter 5

Discussion

5.1 Answering the Research Question

The modeled water requirements and groundwater head data show that current net abstraction in Karnal, Haryana is too high, and has resulted in an annual draw-down of around 75 cm/yr over the last 15 years. Given the disparity between simulated net abstraction and observed groundwater decline the initial assumption that irrigation is purely groundwater based does not hold, and conjunctive use may occur to a greater degree than reflected in literature (Erenstein 2009; Siebert et al. 2010; Kumar Joshi et al. 2021). Other sources of irrigation and recharge also have to be taken into account in further research, as the model only captures around 25 % of recharge as it stands now. If these additional unaccounted sources are factored in, an ET reduction target of 100 mm/yr should be aimed for to reduce annual draw-down to zero. This is in line with findings from Humphreys et al. (2010), that make a similar observation for Gujjarwal in central Punjab (draw-down 1 m/yr; reduction target 150 mm).

The adapted pyfao56 model shows that PTR, as it is currently practiced (and assuming a well established puddle), performs well at limiting deep percolation and utilizing rainfall. Farmers are less dependent on groundwater pumping and the method allows for considerable flexibility in terms of irrigation scheduling. This is likely the reason why it remains the preferred choice of rice cultivation for farmers. The model data shows that the land preparation leads to around 50 mm of evaporation over a 10-day period. This could be reduced further by minimizing puddling operations to 1-2 passes over 2-3 days.

Current DSR practices save around 15 % irrigation water, but most “savings” are return flows to the aquifer (i.e. deep percolation). With an estimated ET reduction target of 10 %, DSR as it is practiced currently (5 % ET reduction over PTR) will not be able to stop the groundwater depletion on its own. DSR is planted 20 to 30 days earlier than the estimated optimal planting dates, resulting in higher ET in the early stages of crop growth, and less residual soil moisture after harvest increases water requirements for the subsequent wheat crop.

Furthermore, irrigation scheduling that does not specifically target ET reduction (deficit irrigation below field capacity in rice) will not have a significant effect on groundwater depletion. AWD scheduling above field capacity, which simply reduces percolation and no effect on net abstraction, is the clear looser of this analysis. This scheduling reduces irrigation by 25 % compared to PTR, but only reduces ET_a by 2 %. What is conceptually clear from Seckler (1996) and Keller et al. (1996), was therefore confirmed empirically through using the FAO56 methodology and the rice-specific pyfao56 implementation. The theory and practice agree. “Wet” water savings require ET cuts.

In the current rice-wheat cropping system in Haryana, these cuts can be achieved in two ways. The multiple regression analysis shows that every 10-day period of delay in transplanting leads to a ET reduction of 50 mm. In this way net abstraction can easily be reduced from over 500 mm in May to below 400 mm in the last dekad of June for all three methods AWD, DSR *and* PTR. Concrete groundwater conservation gains could be made by stricter enforcement of the ban on early transplanting, and including DSR which is currently being sowed around June 1st. Complementary to this, the shortening of the rice growing season by 20 days (e.g. from 140 to 120 days) could lead to a further 70mm reduction and reduce overall crop water requirements.

To answer the main research question. A sole focus on establishment method (direct seeded, transplanted) or irrigation scheduling (continuously flooded, AWD) has no significant effect on net annual aquifer abstraction and the resulting groundwater decline. Rather, a 20 day dealy of direct-seeding *or* transplanting in combination with shorter duration rice varieties (e.g. PB-126; ideally with traits of higher water stress tolerance and higher rates of biomass accumulation) and targeted irrigation (AWD or deficit irrigation below field capacity, with ample water in the critical growth stages) is the way forward. With a careful combination of these measures and including the additional sources of recharge not accounted for in this study, a closure of the recharge deficit (100 mm or 10 % of ET) can be achieved with reasonable certainty.

5.2 Groundwater Sustainability in NW India

Though the modeled results show that there is a real potential for groundwater sustainability in northwest India, they also reveal a significant disconnect between technical potential and practical implementation. While agronomic interventions like DSR and AWD demonstrate water-saving capacity in controlled scenarios, their real-world effectiveness is limited by broader economic and institutional factors. The widely promoted “more crop per drop” paradigm (i.e., decreasing irrigation requirements per unit yield) oversimplifies matters, as it conflates irrigation efficiency gains with actual water conservation. As layed out in theory and corroborated by empirical evidence, most such improvements yield “dry” water savings (reduced percolation) rather than the “wet” savings (reduced ET) needed for aquifer recovery.

5.2.1 The Role of Governance

The disconnect between efficiency gains and actual conservation is rooted in two economic principles: the Jevons Paradox and the rebound effect (York et al. 2015; Sorrell 2009). The Jevons Paradox states that improved efficiency incentivises greater consumption because of lower costs and greater supply. For example, if more water becomes available, farmers are likely to consume more, not less. This leads to a rebound effect where the efficiency gains are offset by increased demand. Recent empirical findings align with these theories. In South India, drip irrigation's efficiency gains led farmers to sell their water quotas, leading to an expansion of the cropping area rather than reduced withdrawals (Fishman et al. 2023). Similar patterns emerged in US irrigation districts, where efficiency gains were redirected to more water-intensive crops (Ward et al. 2008), and in Spain, where pressurized systems enabled cultivation of previously marginal lands (Berbel et al. 2019). Therefore, even when technologies result in field-level water savings, this can not be linearly extrapolated to farm, cropping system or catchment scale. Water savings that increase efficiency will almost certainly be reused somehow or somewhere, and may even stimulate greater total water use if not carefully managed (Ahmad et al. 2014).

Under Haryana's current governance framework, this dynamic might manifest as follows. First, largely unmetered electricity subsidies remove economic constraints on groundwater pumping. The Haryana government covers around 60% of energy costs per kW h totaling to around 700 million USD in 2015 (The Economic Times 2015). Intended to provide financial relief for lower income segments, the subsidy is reported to extend to 20'000 households in the state. Second, the state pledged to expand DSR cultivation to over 12'000 ha by subsidizing DSR with around 120 USD per ha.[1] In total, the commitment would amount to over 14 million USD if fully executed (Agro Spectrum India 2025).

Though intended to foster sustainable managment practices, this subsidy fails to address the underyling risk of farmers overutilizing water resources. Because of the absence of water use monitoring, farmers are not limited in their water use and may end up using "saved" water resources elsewhere. By employing short-duration varieties and taking up triple-cropping for example (e.g. Rice-Parsley-Maize or Rice-Potato-Wheat), the efficiency gains made in rice would be offset. Some progressive farmers with good market access close to the city of Karnal have already launched trials and report good economic results (qualitative farmer survey; Karnal 2024). Additionally, there are no stops in place from preventing farmers from reverting to continuous flooding of DSR or reestablishing paddy rice if DSR crops fail under the current incentive structure of maximizing yield (personal communication; KVK Karnal 2024). This means that in the absence of water accounting and demand-limiting economic constraints on water use, efficiency gains will almost certainly be exploited for production growth — not sustainability.

[1] In comparison, farmers pay anywhere from 1000-2000 USD ha/yr in land rent to landlords (The Times of India 2024).

These realities suggest a clear hierarchy for effective groundwater management. Economic instruments, particularly energy pricing reforms and volumetric water quotas, must form the foundation of conservation efforts. Policy measures, including enforced planting windows and varietal restrictions, should complement these market mechanisms. Technological solutions like DSR and AWD remain relevant but should be deployed as tertiary interventions, ideally incorporating deficit irrigation principles. They can be used to reduce irrigation requirements and reduce financial burdens on institutions. In the face of poor quality of electricity supply and severe load-shedding protocols (Dabadge et al. 2018), these technologies face substantial adoption barriers. They require careful management, including soil-specific scheduling and precise irrigation timing during critical growth stages. Field observations indicate yield penalties of 5-15% compared to PTR, with the risk of severe yield loss increasing for more water-limiting irrigation scheduling like the $-40\,\mathrm{kPa}$ threshold employed in this study.

5.2.2 Policy Recommendations

In terms of groundwater sustainability, two strategies emerge as most viable for immediate implementation:

1. **Delayed transplanting** beyond June 20th, which can reduce ET by 50 mm per 10-day delay through better alignment with monsoon rains.
2. **Short-duration varieties** (100-120 day maturity) that can reduce annual ET by 70 mm through reduced crop duration.

Tripathi et al. (2016) report that the *Preservation of Subsoil Water Act* (2009) has significantly reduced groundwater depletion and the farmer survey from Karnal shows that farmers largely adhere to the early transplanting ban. This should be expanded on. The demand for short-duration high-yielding varieties has sparked the interest of major agricultural companies, and a host of breeding programs have emerged over the last decade (Won et al. 2020). Couched in sensible policy constraints, an expansion on these approaches is well poised to close the recharge deficit and mitigate groundwater decline.[2] They require minimal farmer retraining, maintain yield potential when using improved varieties, and can be administered through existing agricultural extension systems.

The evidence cautions against over-reliance on technological solutions without addressing fundamental economic drivers. As demonstrated by the progressive growers in Karnal testing triple-cropping systems, efficiency gains risk being appropriated for intensification rather than conservation. Sustainable groundwater management in northwest India will ultimately require redefining success metrics from narrow productivity maximization to broader hydrological balance, recognizing that true

[2] It has to be mentioned that the ban on early transplanting has had the unforeseen consequence of severely aggravating air pollution in the region from intensified stubble burning due to less time between rice harvest and wheat sowing to avoid early heat stress in wheat (Balwinder-Singh, McDonald, et al. 2019). Unforeseen consequences like this should be expected and require a broader analysis of trade-offs than presented in this study.

conservation requires reducing consumptive use rather than merely improving application efficiency.

5.3 On Modeling and FAO56

The foundation of this study rests on an adapted version of the pyfao56 model, a Python implementation of the FAO56 soil water balance methodology outline in Chapter 3. This choice was motivated by the need to: (1) maintain physical realism in simulating rice paddies while avoiding the parameterization challenges of more complex models like DSSAT or Hydrus-1D, (2) to enable customization of key hydrological processes specific to northwest Indian cropping systems, and (3) to efficiently generate reproducible results for a large set of scenarios. After implementing the changes, the model simulated daily water balances for rice-wheat-fallow rotations across 30 years of historical climate data (1989-2019), generating 5’670 seasonal water balances through systematic combination of rice, fallow, and wheat; establishment methods (PTR, DSR); irrigation thresholds (flooded, AWD); varietal durations; and planting dates.

5.3.1 Key Model Adaptations

Expanding on the preexisting pyfao56 model (Thorp 2022), the following adaptations were made:

1. Introduced **van Genuchten hydraulic conductivity** (K) to limit percolation in continuously flooded rice paddies and irrigation scheduling above field capacity
2. Added a **Landprep module** to simulate water requirements for rice puddle establishment
3. Added **puddling effects** on saturated hydraulic conductivity (K_{sat}) as implemented in CROPWAT 8.0

The van Genuchten parameters were integrated to better represent percolation dynamics in flooded paddies. This allowed the model to simulate the nonlinear relationship between soil moisture and conductivity, which made it possible to accurately capture the sharp increase in deep percolation above field capacity. Second, the land preparation module simulated the soil water balance during the puddling procedures, which is often overlooked in water accounting and, thirdly, the addition of this module made it possible to simulate puddling effects on saturated hydraulic conductivity (K_{sat}).

Through Python’s object-oriented architecture these adaptations were implemented with relative ease, and the modular code structure allowed for model development where hydrological processes could be inserted without disrupting the core FAO56 algorithms. The complete adapted codebase has been made publicly available on GitHub[3] to facilitate reproducibility and future improvements.

[3]See source-code at: `https://github.com/pahlse/pyfao56-rice`

5.3.2 Design Choices and Tradeoffs

The decision to simulate 30 years of daily water balances (rather than using aggregated climate data) was motivated by the desire to preserve rainfall variability. In northwest India, over 80% of annual precipitation occurs in just 4 months from June to September. During this period, daily percipitation can vary significantly (mean 25 mm, IQR 5-60 m), with some days receiving over 100 mm of rainfall. On average rainfall events occur every 3-4 days and intense rainfalls are interspersed with lower amounts. Standard approaches like splitting monthly totals over 4-5 rainfall events would artificially smooth this variability, which was deemed problematic for DSR systems where heavy rains can trigger percolation rates exceeding 30 mm/day, while the smaller rainfall events may only contributed to soil evaporation. By preserving daily climate resolution, the model could capture these dynamics.

However, this choice came with computational costs. The complete simulation required approximately 3 hours on an 8-core processor, and the subsequent data aggregation proved challenging. But these tradeoffs were justified by the analytical benefits. The high-resolution output enabled the statistical analysis through multiple regression, and the systematic exploration of the parameter space yielded valuable insights into the model's behavior.

5.3.3 Limitations and Future Directions

While the adapted model successfully addressed FAO56's limitations in accurately simulating rice water balances, several limitations remain. As discussed prevoiusly, pyfao56 is a static model. Crop growth is not driven by cumulative temperature (GDD), water stress (Ks) and cumulative leaf area growth. This constrained the ability to fully evaluate yield-ET tradeoffs, particularly for deficit irrigation scenarios. Second, the use of volumetric water content (rather than matric potential) as the primary state variable oversimplifies root zone dynamics, and the one-day timestep and uniform rootzone soil properties limit the accuracy of water flow across the lower boundary.

To improve the pyfao56 model, while keeping true to the FAO56's core methodology, three improvements remain for future work:

1. replace volumetric water content by matric potential head as the primary state variable. This could significantly reduce model complexity.
2. expand soil conductivity functionality to the `SoilProfile` class to allow for spatially variable soil properties and time-varying hydraulic conductivity.
3. include the nursery phase as a seperate module to allow for simulation of the entire rice cropping cycle.

More accurate methodologies like the one used in Aquacrop or the partial differential Richards equation implemented in Hydrus-1D come to mind as alternatives to FAO56. However, they defeat the purpose of using FAO56, which is to provide a simple, transparent, and reproducible model for irrigation scheduling and water balance accounting. Additionally, the development of a graphical user interface (GUI) would improve accessibility for non-programmers.

5.3.4 Reflections on Model Parsimony

The FAO56 methodology's parsimony proved particularly valuable in this study context. By focusing on the most consequential hydrological processes (ET, percolation, irrigation requirements) while excluding less important mechanisms, the model achieved an effective balance between complexity and utility. However, in order to accurately simulate the water balance of rice paddies, the methodology's simplifying assumption on soil physics had to be relaxed slightly. The integration of the van Genuchtens hydraulic conductivity parameters proved easier than expected and turned out to be well-suited to northwest India's data-scarce environment, where many parameters required by more complex models are unavailable or poorly constrained. The model's relative simplicity also reduced the learning curve for users and enhanced interpretability that might have been more challenging with a more sophisticated model.

Ultimately, the pyfao56 model served its intended purpose as a “middle-ground” tool. Being more physically realistic than spreadsheet-based approaches, yet more accessible and adaptable than full-process models like DSSAT or Hydrus-1D, its outputs provide a solid foundation for future research. Additionally, its open-source architecture and modular design encourage collaboration and ensures extensibility as new data, use-cases and understanding emerge.

5.4 Final Recommendations

Sustainable groundwater management requires a fundamental shift from productivity-focused approaches to hydrological balance. By integrating policy, agronomy, monitoring, and research, stakeholders can achieve meaningful reductions in groundwater depletion while maintaining agricultural livelihoods. The following recommendations provide a roadmap for sustainable groundwater management:

1. **Policy and economic reforms** must prioritize reducing evapotranspiration (ET) rather than irrigation efficiency alone. Enforcing delayed rice planting and promoting short-duration varieties can significantly cut annual water consumption. Simultaneously, restructuring energy subsidies – such as introducing tiered electricity pricing (IISD 2022) – would discourage excessive groundwater pumping while protecting smallholder farmers.

2. **Bundled agronomic best-practices** should focus on synergizing water-saving strategies for maximum impact. Combining DSR with deficit irrigation, optimizing land preparation to minimize evaporation, and aligning crop cycles with monsoon rains can reduce net aquifer abstraction. These measures must be complemented by farmer education and monitoring to ensure proper implementation.

3. **Robust water accounting** systems are essential to track groundwater use and enforce conservation. Installing water meters, and implementing district-level monitoring of abstraction and recharge will help assess the real impact of interventions. Integrating crop modeling with groundwater flow analyses can provide a comprehensive understanding of the water balance and inform policy decisions.

4. **Improved modeling and research** can refine decision-making and policy design. These models should be adapted and parameterized for local conditions to benefit farmers and policymakers. Further studies should focus on better soil and crop-specific data availability and further investigate potentials for rebound effects – such as water reuse for triple-cropping – to prevent unintended consequences.

Conclusion

This study employed a parsimonious modeling approach, adapting the FAO56 methodology through the open-source `pyfao56` python package to simulate the potential impact of various water-saving strategies on the soil water balance of a rice-wheat cropping system in northwest India. Key innovations included integrating van Genuchten hydraulic conductivity parameters to better represent paddy hydrology, including water requirements for land preparation and incorporating puddling effects on saturated hydraulic conductivity, features often overlooked in regional water balance studies for rice. The modified Python code, publicly available on GitHub, enables future researchers to simulate rice-specific water balances with improved physical realism. While simplified compared to dynamic models like DSSAT or Hydrus-1D, this approach nonetheless effectively captured system-level interactions between irrigation management, crop phenology, and aquifer recharge. The model's strength lies in its ability to disentangle consumptive water use (ET) from non-consumptive losses (percolation) across diverse management scenarios with limited data requirements and can serve as a tool to provide deeper insights into the limitations and opportunities of prevailing water-saving interventions.

The soil water balance analysis revealed that direct-seeded rice (DSR) and alternate wetting and drying (AWD) achieve only modest reductions in net aquifer abstraction when implemented in isolation. Contrary to common assumptions, their primary water "savings" stem from reduced deep percolation – a non-consumptive loss that is crucial to aquifer recharge in many areas. In Karnal's context, such efficiency gains may inadvertently increase net abstraction if "saved" water is redirected to expanding production. Real conservation requires reducing evapotranspiration (ET), which can be achieved through delayed planting (aligning crops with monsoon onset) and short-duration varieties. These strategies lower irrigation demand without compromising the aquifer's recharge potential.

The path to sustainable groundwater use hinges on recognizing the hierarchy of drivers: economic incentives and policy frameworks outweigh purely technological solutions. Under current conditions – where energy for pumping is heavily subsidized, and yield maximization is prioritized – farmers adopting DSR in combination with short-duration rice varieties may exploit its status as a 'water saving technology' to intensify cropping rather than conserve water. Citing Ward et al. (2008); "achieving real water savings requires designing institutional, technical, and accounting measures that accurately track and economically reward reduced water depletion."

This underscores a paradoxical insight: sometimes, less technological intervention – when coupled with demand-limiting policies – achieves more conservation. While optimized DSR and AWD can contribute to groundwater stabilization, their success depends on embedding them within broader reforms that address the root causes of over-abstraction. For northwest India's intensively utilized water balance, the true test of any intervention lies not in local efficiency gains, but in whether it curbs the systemic depletion of a shared lifeline – a challenging undertaking in any environment.

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