Socio-Hydrological Modeling of Cooperative and Competitive Water Use in Punjab's Traditional Irrigation Networks

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1 Purpose and Patterns

1.1 Purpose

The model simulates farmer behaviour in Warabandi canal irrigation systems, as widely implemented in Punjab and other parts of South Asia. Although the formal system prescribes fixed rotational turns, farmers routinely deviate from these rules through informal sharing, monetary water trades, or theft. The purpose of the model is to examine how landholding inequality, upstream–downstream positioning, social relationships, economic constraints, and hydrological variability (seasonal patterns, random fluctuations, droughts, and floods) jointly shape farmers' behavioural strategies. By explicitly representing these socio-hydrological feedbacks, the model aims to identify the conditions under which cooperative water governance is sustained or undermined, and to explain the resulting patterns of agricultural performance, economic inequality, and social capital.

1.2 Patterns

The following macro-level patterns are expected to emerge from the interaction of individual rules and are the primary phenomena the model seeks to reproduce:

- Persistent advantage and wealth accumulation among upstream farmers and larger landholders due to lower conveyance losses and reduced exposure to theft.
- Marked increases in water theft during periods of low flow, drought, or high supply variability.
- Higher rates of water sharing and trading when crop-growth stages are staggered across the community.
- Greater adoption of high-risk strategies (notably theft) by downstream and small-scale farmers facing chronic water deficits.
- Progressive erosion of social networks — declining friendship strength, falling social credit, and dissolution of ties — following repeated theft or imbalanced exchanges.
- Infrequent but severe punishment when theft is detected, allowing low-level illegal extraction to persist.
- Accelerated growth in wealth inequality (higher Gini coefficients) under regimes of scarce or highly variable water supply.
- Strengthening of cooperative relationships and more balanced trading during seasons of abundance or when cropping calendars are synchronised.

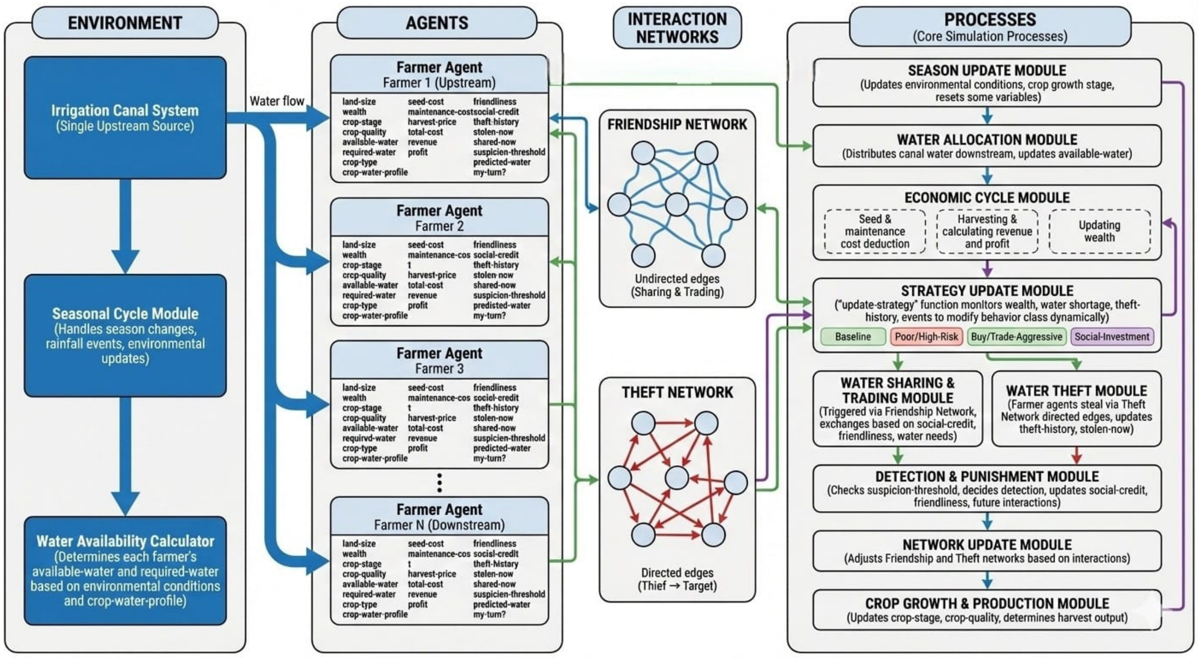

Figure 1: System flow diagram illustrating the core components and process structure of the agent-based irrigation model.

2 Entities, State Variables, and Scales

2.1 Entities

The model comprises the following entity types:

- **Farmers** (breed: `farmers`): heterogeneous agents representing individual landholders.
- **Friendships** (undirected link breed): persistent social ties used for water sharing and trading.
- **Thefts** (directed link breed): temporary links created each week to record and visualise ongoing water theft.
- **Patches**: a simplified spatial environment in which the leftmost column (`pxcor = min-pxcor`) represents the irrigation canal, and rows correspond to individual farmers ordered from upstream (low `ycor`) to downstream (high `ycor`). The last 4 cells of each row with a farmer, represent (in order from left to right), their wealth (red to green), social credit (red to green), number of times robbed without noticing (dim to bright orange), number of times they have taken water through sharing or purchasing (dim to bright blue).

2.2 State Variables

State variables for each entity are listed below. Variables that change during the simulation are marked with an asterisk (*).

2.2.1 Farmers

- `ycor` — upstream–downstream position (fixed after setup)
- `land-size` — farm size in acres (log-normally distributed, 3–29 acres; fixed)
- `wealth`* — cash holdings in PKR
- `living-cost` — weekly household expenditure (scaled by land-size; fixed)
- `social-credit`* — community trust level (-10 to +10)

- `friendliness`* — inherent generosity (0–1)
- `crop-type`* — current crop (rice, cotton, wheat, or mustard)
- `crop-stage`* — weeks since planting (or weeks to start planting if negative)
- `crop-quality`* — cumulative quality multiplier (0.3–2.0)
- `crop-water-profile`* — weekly per-acre water requirement vector for the current crop
- `required-water`* and `available-water`* — water demand and receipt this week
- `seed-cost`, `maintenance-cost`, `harvest-price`, `total-cost`* — economic parameters for the current season
- `revenue`* — realised income at harvest
- `current-strategy`* — adaptive behavioural class (Baseline, Poor/High-Risk, Buy/Trade-Aggressive, Social-Investment)
- `share-aggressiveness`* and `p-steal-base`* — strategy-dependent modifiers of sharing and theft probabilities
- `suspicion-threshold`* — tolerance for water shortfall before theft inquiry
- bookkeeping variables (`shared-now`, `stolen-now`, `theft-history`, etc.)

2.2.2 Friendships (undirected links)

- `end1`, `end2` — the two connected farmers
- `strength`* — tie strength (0–1), evolves with use and imbalance
- `water-a-to-b-balance`* — net water transferred from `end1` to `end2`

2.2.3 Thefts (directed links, recreated each tick)

- `end1` (thief) → `end2` (victim)
- `amount-stolen`* — volume of water stolen this week

2.2.4 Global environment

Key globals include `total-flow`*, `rainfall-factor`*, `growth-efficiency`*, season (`"rabi"` or `"kharif"`), week number, and aggregate counters (`total-thefts`, `detected-thefts`, `trade-volume`, etc.).

All other model parameters are exposed as user-adjustable sliders; their default values and roles are listed in Table 1.

2.3 Scales

- **Spatial scale:** Each patch with `pxcor > min-pxcor` represents one acre of farmland; the leftmost column (`pxcor = min-pxcor`) is the irrigation canal.
- **Temporal scale:** One tick = one week.
- **Simulation duration:** 520 ticks (10 years), with Rabi and Kharif seasons alternating every 26 weeks.

3 Process Overview and Scheduling

3.1 Processes

The model proceeds weekly through a fixed sequence of processes, all executed by the observer and applied to farmers (and their links) in a defined order:

- **Seasonal update and crop assignment** (week 1 of new season only) – switches between Rabi and Kharif, deducts seed/maintenance costs, and farmers choose crops strategically based on wealth.
- **Environmental events** – random weekly occurrence of flood, heavy rain, or drought; adjusts `rainfall-factor` and `growth-efficiency`.
- **Water supply and allocation** – updates `total-flow` (seasonal + environmental + random), allocates water proportionally to land size with progressive downstream losses (kacha system/unlined watercourses) and randomness.
- **Economic deductions** – weekly water fees and living costs are subtracted from `wealth`.
- **Strategy update** – each farmer reassesses current water deficit and wealth to adopt one of four behavioural strategies.
- **Water sharing and trading** – farmers with deficits first attempt paid purchases, then request sharing via friendship links (logistic acceptance probability) through implicit promises to return the favor in the future.
- **Water theft** – deficit farmers probabilistically steal from downstream victims (logistic probability based on deficit, social credit, tie strength, etc.); up to three attempts per farmer.
- **Theft detection** – victims compare received vs. expected water estimated by querying an upstream friend; if discrepancy exceeds suspicion threshold, a probabilistic detection is run for each theft. If theft is caught, then the corresponding stolen water is returned, and the thief is penalised.
- **Network evolution** – weak friendships (`strength` < 0.05) are dissolved and replaced.
- **Crop growth and harvest** – crop stage and quality updated based on water received; harvest occurs automatically when the crop reaches its final stage.

3.2 Scheduling

All processes are executed **asynchronously** in the exact order listed above, once per tick (week). Water theft is processed from upstream to downstream (using the fixed `farmer-order` list) to correctly simulate flow direction and opportunity. All other farmer-level updates (strategy, sharing requests, growth) occur in a random order. Temporary directed `thefts` links are cleared at the beginning of each tick. The simulation runs for exactly 520 ticks (10 years) or until manually stopped.

4 Design Concepts

4.1 Basic Principles

The model is grounded in socio-hydrological theory and empirical observations of Punjab's Warabandi irrigation systems: formal water rotations are routinely bypassed through informal sharing, trading, or theft. Behaviour is driven by bounded rationality, resource scarcity, social relationships, and economic costs. Upstream–downstream positioning and landholding inequality create structural power imbalances, while hydrological variability introduces stochastic stress.

4.2 Emergence

Macro-level patterns — dominance of particular strategies, persistence or collapse of cooperative networks, seasonal spikes in theft, and overall crop performance — emerge entirely from local rules of water allocation, sharing, theft, detection, and economic feedbacks. No top-down controls are imposed.

4.3 Adaptation

Each week, farmers dynamically switch among four behavioural strategies (Baseline, Poor/High-Risk, Buy/Trade-Aggressive, Social-Investment) based on current water deficit and wealth relative to seasonal costs. These strategies alter sharing aggressiveness, base theft probability, and social-investment tendencies.

4.4 Objectives

Farmers implicitly aim to maximise long-term wealth (and survival) by securing sufficient water each week while minimising economic and social penalties. Success is measured internally through realised profit and externally through wealth accumulation and sustained social credit.

4.5 Sensing

Farmers sense:

- their own water deficit, available water, wealth, and current strategy,
- for each friendship neighbour: surplus/deficit, friendship strength, and past water-trade balance,
- for potential theft victims (downstream): land size, approximate water holdings, social credit, wealth, and friendship strength (if a friendship exists),
- global environmental cues indirectly via received water and detected discrepancies.

They do not observe exact values of distant agents or future flows.

4.6 Interaction

Direct interactions occur via:

- friendship links (requests for sharing/trading, monetary transfers, balance updates),
- directed theft links (unilateral water extraction),
- theft detection and punishment (water return + fines).

Indirect interaction arises through downstream water losses and aggregate scarcity.

4.7 Stochasticity

Randomness is used for:

- initial land-size (log-normal), friendliness, and social credit,
- crop-stage offset at planting,
- weekly water allocation fluctuations and downstream loss variation,
- occurrence and intensity of floods, heavy rain, and droughts,
- friendship formation, sharing acceptance, theft success, and detection inquiries, detection success,
- tie dissolution and replacement when strength falls below threshold.

Stochasticity represents unobserved heterogeneity and environmental unpredictability.

4.8 Collectives

Friendship networks form persistent collectives that facilitate cooperation and information flow. Weak ties are periodically dissolved and replaced, allowing network topology to evolve endogenously. No formal groups or hierarchies exist beyond the upstream–downstream ordering.

4.9 Observation

Model behaviour is observed in real time through the following monitors and plots in the NetLogo interface (Figure 2) :

- **Aggregate counters (monitors):** total-thefts, detected-thefts, total-trades, trade-volume, total-theft-checks, dropped-friendships
- **Social and behavioural monitors:** avg friendship strength, friendliness, social credits of farmers, sus-threshold
- **Economic monitors:** min [wealth] of farmers, max [wealth] of farmers
- **Environmental/seasonal monitors:** total-land, season (kharif/rabi)
- **Time-series plots:**
  - Water Required (green line)
  - Crop Quality (red line)
  - Social Credits of Farmers (black declining line)
  - Water Incoming (oscillating black line)
  - Friendship Balance (distribution)
  - Total Thefts vs Detected Thefts (blue/red lines)
- **Distribution and composition plots:**
  - Wealth Distribution (histogram with red bars)
  - Wealth Variance (time series)
  - Strategy (stacked area: Poor/High Risk in red, Buy/Trade-Aggressive in green, Social-Investment in blue, Baseline in black)

All plots update weekly. Complete time-series and final distributions are exported via NetLogo's BehaviorSpace for quantitative analysis of inequality, cooperation, and behavioural dynamics.

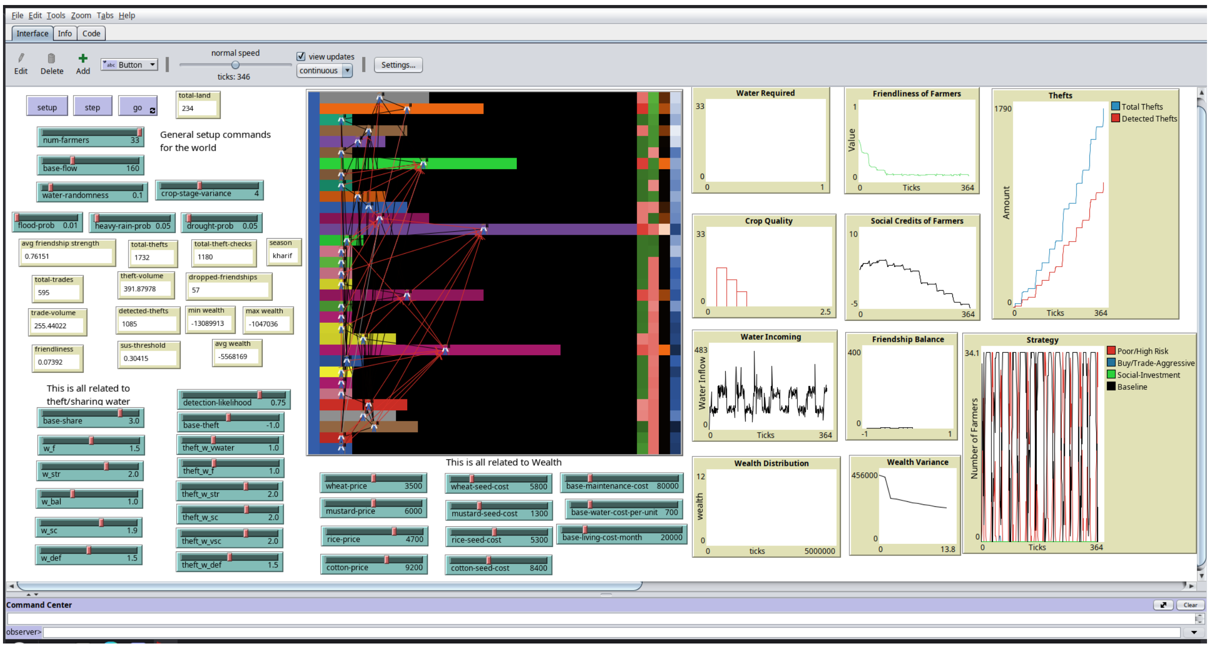

Figure 2: NetLogo model interface showing real-time monitors and plots used for observation during simulation runs.

5 Initialization

At the start of each simulation run, the model is initialised as follows:

- **Farmers:** `num-farmers` agents (default 30, range 10–80) are created. Each farmer receives:
  - `land-size` drawn from a log-normal distribution ($\mu = 1.5$, $\sigma = 0.8$), truncated and rounded to integers between 3 and 29 acres.
  - Initial `wealth` = `land-size` × 20,000 PKR.
  - `friendliness` ∼ Uniform$[0, 1]$.
  - `social-credit` = ln(`land-size` + 1) + Uniform$[0, 0.5]$ (larger landowners start with higher social standing).
  - `suspicion-threshold` ∼ Uniform$[0.05, 0.25]$.
  - Weekly `living-cost` scaled by land-size tier:
    small (< 7 acres) → 0.5×, medium (7–14) → 1×, large (≥ 15) → 1.5× base-living-cost-month.
  - A unique vertical position (`ycor`) determining upstream–downstream order (lower ycor = upstream).

- **Social network (friendships):** Each farmer forms three types of undirected friendship links:
  - Upto two with their immediate spatial neighbour (adjacent ycor, no wrapping),
  - Two with farmers having the most similar `social-credit`,
  - One with a randomly chosen other farmer.

  Initial link `strength` = product of both farmers' `friendliness`; `water-a-to-b-balance` = 0.

- **Crops and planting:** The simulation begins in the Rabi season (week 1). All farmers immediately undergo crop assignment via `assign-crops`:
  - each strategically selects between wheat/mustard (Rabi) based on current wealth, estimated profitability, and water requirements,
  - seed and full-season maintenance costs are deducted from `wealth` at planting,
  - initial `crop-stage` is uniformly offset by - `crop-stage-variance` to + `crop-stage-variance` weeks (default 4) to stagger planting dates across the community,
  - `crop-quality` starts at 1.0.

- **Environment and water supply:** `season` = "rabi", `week` = 1, `total-flow` = `base-flow` (default 160 acre-feet/week), `rainfall-factor` = 1.0, `growth-efficiency` = 1.0, all event counters zeroed.

- **Spatial layout:** The world is a grid where the leftmost column (`pxcor = min-pxcor`) is the irrigation canal (visual only). Each farmer's land extends rightward from `pxcor = 1` for `land-size` patches (1 patch = 1 acre), with the last 4 patches of the row identifying farmers wealth, social credit, times robbed, and times borrowed water.

All random elements (land-size, friendliness, social-credit offset, crop-stage stagger, friendship formation) use NetLogo's built-in random number generator.

6 Input Data

The model does not use input data to represent time-varying processes.

Static parameters, such as crop prices, seed and maintenance costs, are derived from agricultural reports and other sources, and remain constant throughout the simulation [5, 6, 7, 8].

7 Outputs

7.1 High Water Base Flow

Below is the attached output with when the base flow is set to 450

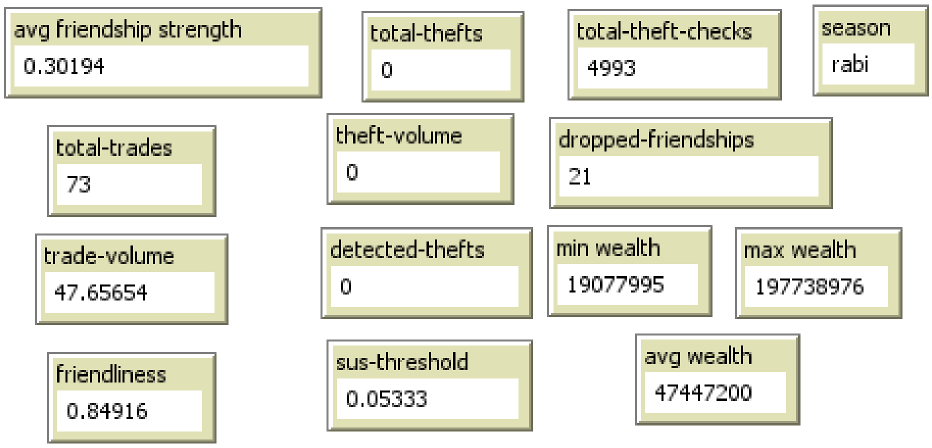

Figure 3: Numerical values corresponding to high base water flow conditions.

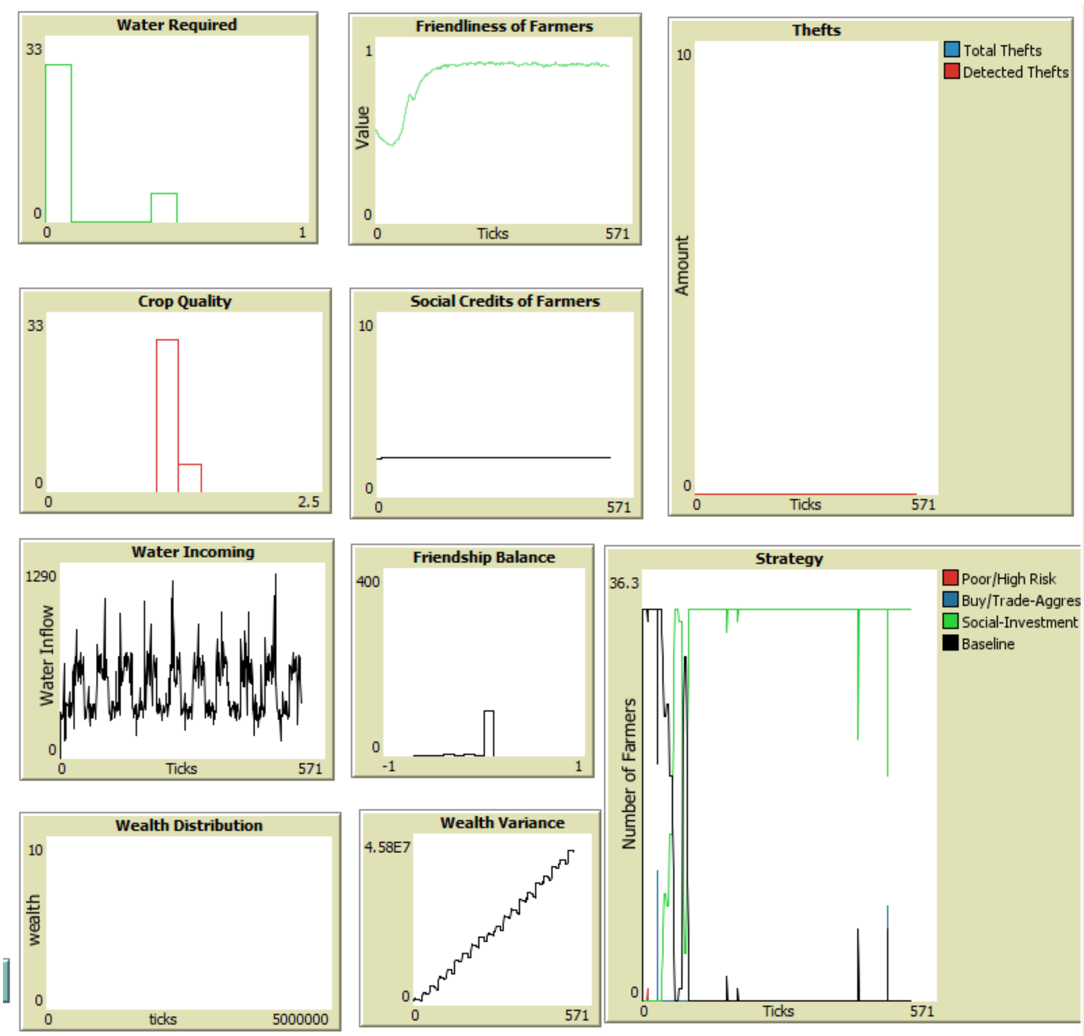

Figure 4: Plots illustrating system behavior under high base water flow conditions.

7.2 Medium Water Base Flow

Below is the attached output with when the base flow is set to default 160

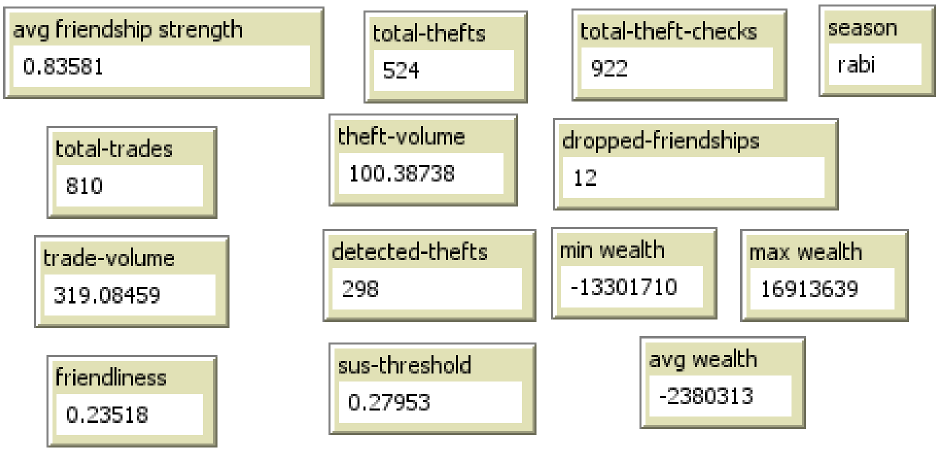

Figure 5: Numerical values corresponding to medium base water flow conditions.

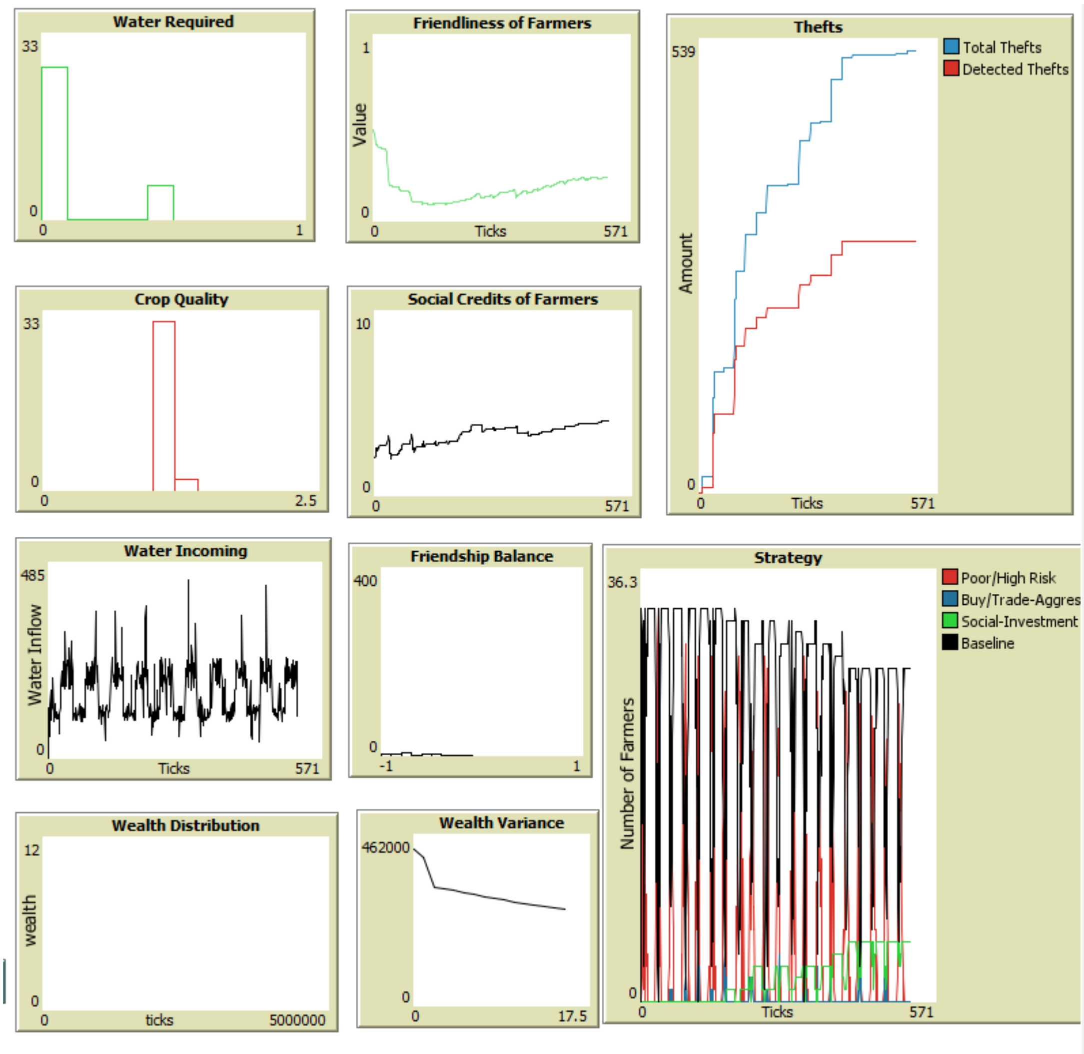

Figure 6: Plots illustrating system behavior under medium base water flow conditions.

7.3 Low Water Base Flow

Below is the attached output with when the base flow is set to 40

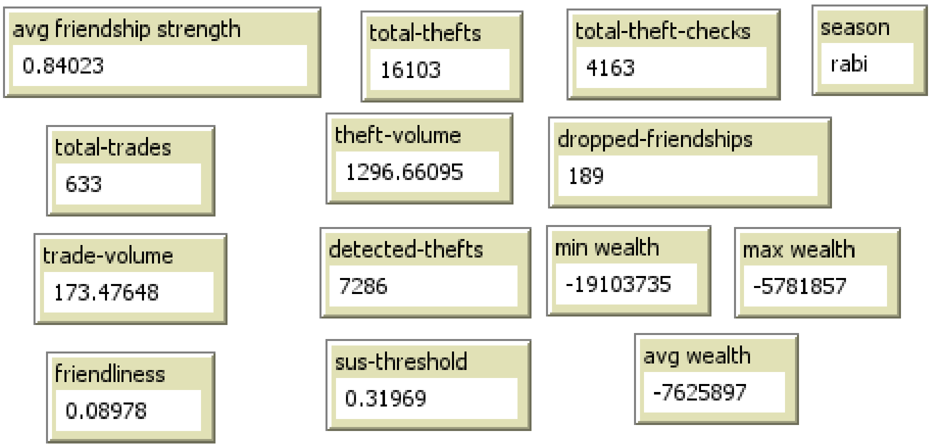

Figure 7: Numerical values corresponding to low base water flow conditions.

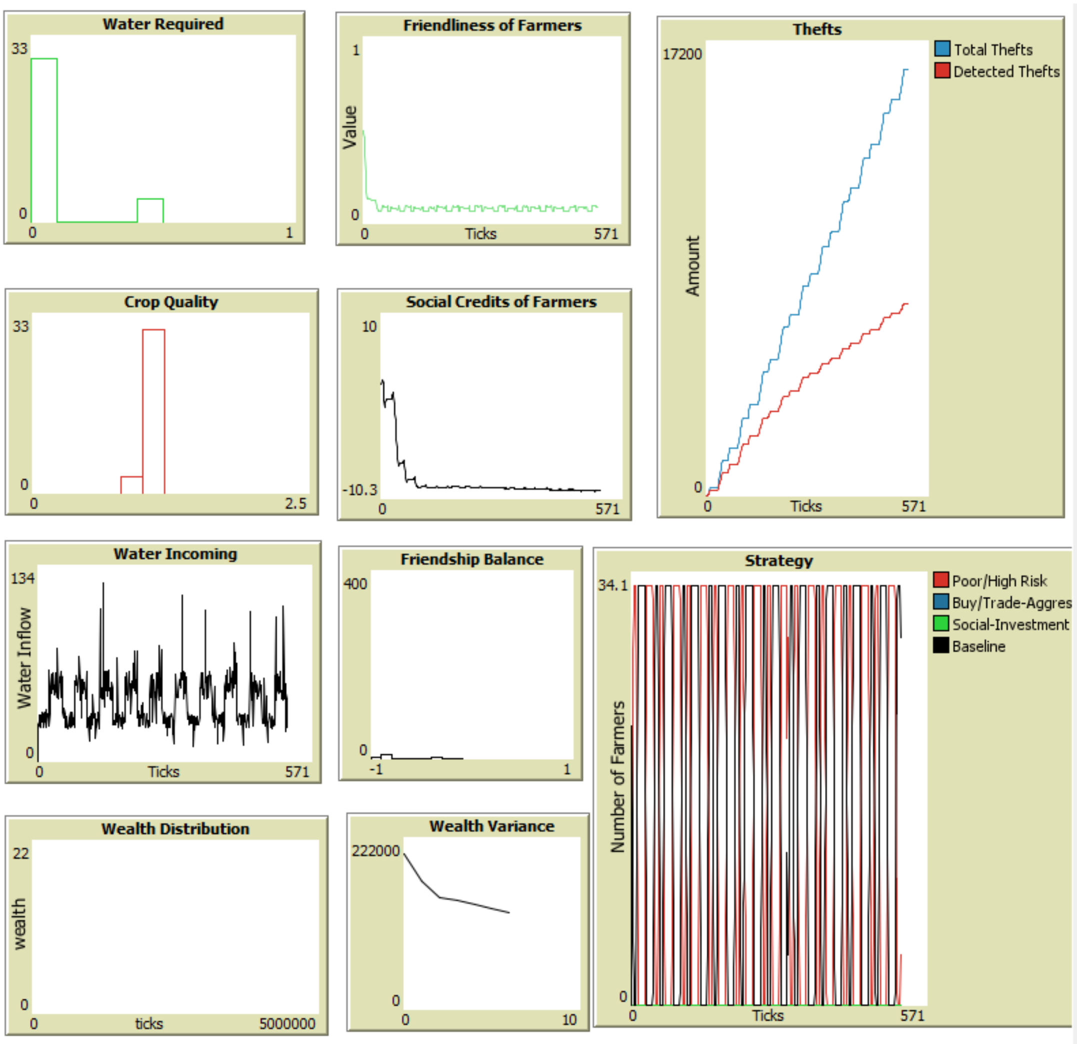

Figure 8: Plots illustrating system behavior under low base water flow conditions.

8 Model Parameters

All tunable model parameters are exposed as sliders in the NetLogo interface. Table 1 lists each parameter, its default value, plausible range, units, and a brief description. Default values are calibrated to reflect typical conditions in Punjab warabandi canal commands (acreage distribution, crop economics, water availability, and observed social behaviours) [5, 6, 7, 8]. These parameters are systematically varied in the sensitivity analysis and BehaviorSpace experiments accompanying the model.

Table 1: Complete list of model parameters exposed as interface sliders

Parameter	Default	Range	Description (units)
`num-farmers`	33	10–33	Number of farming households
`base-flow`	160	50–500	Baseline canal inflow (acre-feet/week)
`water-randomness`	0.10	0–0.40	Random weekly fluctuation in allocation
`crop-stage-variance`	4	0–8	Max initial stagger in planting dates (weeks)
`flood-prob`	0.01	0–0.10	Probability of flood event
`heavy-rain-prob`	0.05	0–0.20	Probability of heavy rainfall event
`drought-prob`	0.05	0–0.25	Probability of drought event
Kharif crops (PKR)			
`rice-price / seed-cost`	4700 / 5300	4000–7000	Price per 40-kg bag / seed cost per acre
`cotton-price / seed-cost`	9200 / 8400	5000–14000	Price per 40-kg bag / seed cost per acre
Rabi crops (PKR)			
`wheat-price / seed-cost`	3500 / 5800	3000–7600	Price per 40-kg bag / seed cost per acre
`mustard-price / seed-cost`	6000 / 1300	1000–6500	Price per 40-kg bag / seed cost per acre
Economic parameters			
`base-maintenence-cost`	80,000	50k–150k	Seasonal maintenance cost per acre (PKR)
`base-water-cost-per-unit`	700	400–2000	Weekly water fee per acre-foot (PKR)
`base-living-cost-month`	20,000	10k–60k	Base monthly household cost (PKR)
Sharing logistic weights			
`base-share`	3.0	-5–5	Intercept in sharing acceptance function
`w-f / w-str / w-bal`	1.5 / 2.0 / 1.0	0–3	Weights: friendliness / strength / balance
`w-sc / w-def`	1.9 / 1.5	0–3	Weights: social credit / deficit
Theft logistic weights			
`base-theft`	-1.0	-5–5	Intercept in theft probability function
`theft-w-def / theft-w-vwater`	1.5 / 1.0	0–3	Weights: thief deficit / victim water
`theft-w-str / theft-w-sc / theft-w-vsc`	2.0	0–3	Weights: strength / thief credit / victim credit
`theft-w-f`	1.0	0–3	Weight: friendliness
`detection-likelihood`	0.75	0.1–1	Likelihood of catching theft

9 Submodels

The submodels correspond to the weekly processes described in the scheduling section. The model distinguishes between two agricultural seasons: *Kharif* (Rice, Cotton) and *Rabi* (Wheat, Mustard), switching every 26 weeks.

1. **Environmental events**
   At the start of a week, an event is determined probabilistically based on mutually exclusive probabilities.
   - **Flood** ($p =$ `flood-prob`): Flow multiplier $\sim U[1.5, 2.3]$, growth efficiency drops to 0.8.
   - **Heavy Rain** ($p =$ `heavy-rain-prob`): Flow multiplier $\sim U[1.2, 1.7]$, growth efficiency drops to 0.9.
   - **Drought** ($p =$ `drought-prob`): Flow multiplier $\sim U[0.4, 0.8]$; available water is further reduced by this factor, growth efficiency drops to 0.9.

- **Normal**: Flow multiplier 1.0, growth efficiency 1.0.

2. **Water supply and allocation**
Total inflow (Q_{total}) is derived from a base flow, seasonal factors ($s_f = 1.3$ for Kharif, 0.7 for Rabi), and environmental fluctuations:

$$Q_{\text{total}} = \texttt{base-flow} \times s_f \times \texttt{rainfall-factor} \times (0.8 + 0.4 \cdot U[0,1])$$

Water is distributed to farmer i based on land size A_i, subject to downstream conveyance losses linearly proportional to the y-coordinate:

$$W_{i,\text{avail}} = A_i \times \frac{Q_{\text{total}}}{\sum A} \times (1 - 0.01 \cdot y_i) \times (1 + \epsilon)$$

where $\epsilon \sim U[-\frac{\texttt{rand}}{2}, +\frac{\texttt{rand}}{2}]$ represents local water randomness. A weekly water fee ($W_{i,\text{avail}} \times \texttt{base-cost}$) is deducted from wealth.

3. **Crop assignment (Seasonal)**
At the start of a season ($t = 1, 27 \ldots$), farmers calculate the *Total Estimated Cost* (C_{est}) and *Max Revenue* ($R_{\max}$) for available crops. Crop choice follows a bounded rationality model based on current wealth W_i:

   - **Secure** ($W_i > 2 \cdot C_{\max}$): Selects the crop with maximum expected profit.
   - **Stressed** ($W_i < 1.5 \cdot C_{\max}$): Selects the crop with maximum water-use efficiency (profit per unit of water).
   - **Default**: Random selection among affordable options.

Seeds and maintenance costs are deducted immediately upon assignment.

4. **Crop growth**
Daily water requirement W_{req} is interpolated from crop-specific water profiles based on the current `crop-stage`. Growth is determined by a clamped multiplier M:

$$M = \min\left(1.2, \max\left(0.8, \frac{W_{i,\text{avail}}}{W_{i,\text{req}}}\right)\right)$$

State updates occur weekly:

$$\begin{aligned} \texttt{quality}_{t+1} &= \texttt{quality}_t \times M \\ \texttt{stage}_{t+1} &= \texttt{stage}_t + (M \times \texttt{growth-efficiency}) \end{aligned}$$

Harvest generates revenue $R = \texttt{quality} \times A_i \times 40 \times P_{\text{market}}$ when the stage exceeds the profile length.

5. **Strategy adaptation**
Farmers update strategies weekly based on deficit stress (D_{stress}) and wealth thresholds.

   - **Poor/High-Risk** ($W_i < 1.5 C_{\text{est}}$ AND $D_{\text{stress}} > 0.2$): Increases theft base probability ($\texttt{p-steal} + D_{\text{stress}}$), increases sharing aggressiveness, and reduces friendliness.
   - **Buy/Trade-Aggressive** (Not Poor AND $D_{\text{stress}} > 0.2$): Drastically increases sharing aggressiveness (+1.5).
   - **Social-Investment** (Rich AND Low Deficit): Reduces theft probability, increases friendliness, and increases suspicion thresholds.

6. **Water sharing and trading**
The process occurs in two sequential phases each week:

   (a) **Direct Purchase/Gift:** Farmers iterate through friends sorted by tie strength.
      - If strength ≥ 0.95: Surplus water is gifted immediately (up to the deficit amount).
      - If strength < 0.95: Water is purchased at `base-cost` per unit, provided the requester has sufficient wealth ($W_{\text{wealth}} \geq$ cost).

(b) **Probabilistic Request:** If a deficit persists, farmers initiate social requests. The probability of asking depends on water stress and strategy:

$$P(\text{ask}) = \frac{1}{1 + \exp\left(-(8 + \alpha_{\text{strat}}) \cdot \left(1 - \frac{W_{\text{avail}}}{W_{\text{req}}}\right)\right)}$$

where α_{strat} is the strategy-based aggressiveness. If asked, a donor accepts with probability:

$$P(\text{accept}) = \frac{1}{1 + \exp(-Y)}$$

where the decision logit Y combines social and historic factors:

$$Y = \texttt{base} + 2w_f(f_{\text{donor}} - 0.5) + 2w_s(s_{ij} - 0.5) + w_b B_{ij} + 0.1 w_{sc} SC_{\text{req}} + w_d \frac{D_{\text{req}}}{W_{\text{req, req}}}$$

Here, f_{donor} is the donor's friendliness, B_{ij} is the historical water balance (positive if the requester is owed), and SC_{req} is the requester's social credit. Successful probabilistic trades are recorded in the link balance B_{ij} without monetary exchange, and capped at 50% of the donor's surplus.

7. **Water theft**
Farmers with deficits identify potential downstream victims. Candidates are sorted by a heuristic H to maximize gain and minimize social risk:

$$H = W_{\text{victim}} - 0.05 \cdot SC_{\text{victim}} - 0.3 \cdot s_{ij}$$

Theft occurs with probability:

$$P(\text{theft}) = \frac{1}{1 + \exp(-X)}$$

where the logit X is defined as:

$$X = \texttt{p-base} + w_d \frac{D_{\text{self}}}{W_{\text{req}}} + w_v \frac{W_{\text{vic}}}{10} - 2w_f(f_{\text{self}} - 0.5) - w_{sc} \frac{SC_{\text{self}}}{10} - w_{vsc} \frac{SC_{\text{vic}}}{10} - w_s s_{ij} - P_{\text{size}}$$

Here, D_{self} is the thief's deficit, W_{vic} is the victim's water, s_{ij} is the tie strength, and $P_{\text{size}} = 0.05 \cdot (A_{\text{vic}}/10)$ is a penalty based on the victim's land size. Successful theft transfers $\min(D_{\text{self}}, 0.2 \cdot W_{\text{vic}})$.

8. **Theft detection and punishment**
Victims randomly query one upstream friend. If the ratio of water-to-land deviates significantly from the friend's ratio (beyond a `suspicion-threshold`), a detection check is triggered (costing 5000 wealth). If detected:

   (a) Stolen water is returned.

   (b) Thief pays a penalty: $P = \text{cost} \times \text{amount} \times (2 + \frac{A_{\text{thief}}}{10})$.

   (c) Thief's social credit reduces by $\max(0.3, \text{current} \rightarrow -10)$.

   (d) Suspicion threshold reduces, due to an increase in paranoia (increases threshold if no theft).

9. **Network evolution**
Friendship ties with strength < 0.05 are dissolved. The unlinked agent initiates a new tie with a random non-neighbor, resetting strength based on mutual friendliness.

10 Assumptions and Limitations

10.1 Assumptions

The model is based on several simplifying assumptions to make simulation tractable while capturing key socio-hydrological dynamics:

- Canal conveyance losses increase linearly with downstream distance; complex hydraulic interactions are not explicitly modeled.

- Farmers attempt a maximum of three thefts per week.
- Water-sharing and trading decisions depend only on social ties, water deficit, and wealth; other negotiation mechanisms are ignored.
- Crop prices, seed costs, and maintenance costs are assumed constant within a season and reflect typical conditions in Punjab.
- The social network evolves only through friendship tie strength and dissolution; broader social or political influences are not included.
- Environmental stochasticity (rainfall, droughts, floods) is represented probabilistically rather than through detailed hydrological modeling.

10.2 Limitations

The model does not capture certain real-world processes or dynamics, including:

- Groundwater extraction or irrigation outside the Warabandi system.
- Market dynamics beyond the fixed crop prices and water fees used in the simulation.
- Policy interventions, subsidies, or enforcement mechanisms beyond the modeled theft detection and penalties.
- Detailed soil heterogeneity, crop-specific water stress responses, or micro-climatic effects.
- Farmer learning beyond the defined behavioural strategies; cultural, familial, or historical influences are not modeled.

References

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