

Appendix A: Complete Model Equation Documentation with Theoretical Grounding

The Delayed Reward Trap: A System Dynamics Archetype for Aspiration-Driven Livelihood Transitions and Its Application to Climate Adaptation Monitoring

A.1 Overview

This appendix provides complete formula derivations and theoretical citations for all 7 stocks, 9 flows, and 18 key auxiliary variables in the synthesis stock-and-flow diagram (SFD). The model was built in Ventana Systems Vensim and operationalizes the 13-loop Delayed Reward Trap archetype described in Section 5. Every mathematical component is justified by published literature; the document is organized to serve as a standalone technical record for reviewers and replication.

Model file: my.mdl. Time horizon: 25 years. TIME STEP: 0.0078125 years (1/128 year). Integration method: Euler. All monetary values in generic currency units (dimensionless ratio behavior is invariant to currency scale). Population in households.

A.2 Stocks (7 Variables)

All stocks follow the fundamental accumulation identity (Forrester, 1961, Eq. 3.1; Sterman, 2000, Eq. 6-1):

$$\text{Stock}(t) = \text{Stock}(t_0) + \int [\text{Inflow}(s) - \text{Outflow}(s)] ds$$

Integration creates system memory and path-dependence absent from purely algebraic formulations. Stocks can only change through flows; this is the structural source of delay dynamics in the model.

A.2.1 Traditional Livelihood Households

Equation:

$$\text{Traditional_Livelihood_Households} = \text{INTEG}(\text{Reverse_Transition} - \text{Transition_Rate}, 900)$$

Initial value: 900 households

The 90/10 split between traditional (900) and new (100) livelihood households at $t = 0$ reflects the innovator/early-adopter phase of Rogers' (1962) diffusion S-curve (cumulative adoption $\approx 16\%$). All case studies document small initial bases: Nepal vegetable production rising from 2010/11 implies a minority practice initially (MoALD, 2020); Myanmar case studies similarly document secondary vocation holders as a small minority of farming households at programme baseline.

The population might change but total number of households is constant, consistent with a 15 year program cycle. Conservation requires $\text{Traditional_HH} + \text{New_HH} = 1,000$ for all t , which the flow structure automatically enforces: $d(\text{Traditional})/dt + d(\text{New})/dt = (\text{Reverse} - \text{Transition}) + (\text{Transition} - \text{Reverse}) = 0$ (Sterman, 2000, Ch. 12, pp. 429–431).

Key citations:

Forrester (1961, p. 68–69); Sterman (2000, Eq. 6-1, pp. 192–194, Ch. 12 pp. 429–431); Rogers (1962, Ch. 7); Bass (1969, Eq. 1).

A.2.2 New Livelihood Households

Equation:

$$\text{New_Livelihood_Households} = \text{INTEG}(\text{Transition_Rate} - \text{Reverse_Transition}, 100)$$

Initial value: 100 households

Mirror structure to Stock 1. This is the coflow formulation of Forrester (1961, Ch. 8): any flow draining one stock fills the other.

Key citations:

Sterman (2000, Ch. 12 pp. 429–431); Bass (1969, Eq. 1, p. 216); Rogers (1962, Ch. 7); Hirschman (1970, Ch. 1–2) for reversibility justification.

A.2.3 Enabling Infrastructure

Equation:

$$\text{Enabling_Infrastructure} = \text{INTEG}(\text{Construction} - \text{Commissioning}, 400)$$

Initial value: 400 capacity units

This stock represents infrastructure under construction but not yet operational (irrigation canals being dug, energy installations being built). It cannot be used by households; it contributes to productivity only once it commissions into Functional Infrastructure. The two-stock pipeline structure implements a second-order delay, producing bell-shaped completion-time distributions that are more realistic than the exponential distribution implied by a first-order formulation (Sterman, 2000, pp. 422–424).

The non-zero initial value (400 units) ensures the simulation begins with projects already in progress, avoiding a discontinuity at $t = 0$. The initial surplus (650 total / 100 required = 6.5x) supports the growth phase before constraints bind.

Key citations:

Sterman (2000, pp. 419–426, Ch. 11 Section 'Pipeline Delays', Eq. 11-7); Lyneis and Ford (2007, Section 3.2, pp. 167–170); Forrester (1961, Ch. 8 'Coflows').

A.2.4 Functional Infrastructure

Equation:

$$\text{Functional_Infrastructure} = \text{INTEG}(\text{Commissioning} - \text{Functional_Depreciation}, 250)$$

Initial value: 250 capacity units

This stock represents operational infrastructure that households can use: completed irrigation schemes (Nepal), functioning solar/grid energy installations (Myanmar). Productivity, climate destruction, and the Latency Matching constraint all reference this stock, not Enabling Infrastructure. The initial 250 units against 100 New_HH (2.5x requirements) creates a buffer for the early growth phase.

Depreciation has two independent components:

Component 1 — Normal depreciation (continuous wear-and-tear):

$$\text{Normal_Depreciation} = \text{Functional_Infrastructure} / \text{Infrastructure_lifetime}$$

This implements exponential decay $dK/dt = -K/\tau$, the standard capital accumulation equation from Solow (1956, Eq. 1, p. 66) and Sterman (2000, Eq. 10-2, p. 386). With Infrastructure_lifetime = 10 years, the annual depreciation rate is 10%.

Component 2 — Climate event destruction (discrete pulse):

$$\text{Climate_Infrastructure_Destruction} = \text{Climate_event_occurs} \times \text{Functional_Infrastructure} \times \text{Infrastructure_damage_fraction} / \text{TIME_STEP}$$

Division by TIME_STEP converts the fractional stock destruction into the instantaneous rate required by SD integration. Dividing by the Vensim TIME_STEP variable (rather than a hardcoded constant) ensures the destruction rate scales correctly if the simulation step size changes. This is documented by Herrera de Leon and Kopainsky (2019) for discrete event modelling in SD.

Key citations:

Solow (1956, p. 66); Sterman (2000, Eq. 10-2, p. 386, Ch. 11 pp. 419–426); Herrera de Leon and Kopainsky (2019) for discrete infrastructure damage; Lyneis and Ford (2007).

A.2.5 Perceived Income

Equation:

$$\text{Perceived_Income} = \text{INTEG}(\text{income_perception_change}, 60000)$$

$$\text{income_perception_change} = \text{MAX}(0, (\text{Mean_income_per_household} - \text{Perceived_Income}) / \text{Perception_delay})$$

Initial value: 60,000 currency/HH/year

This stock implements a first-order information delay with an asymmetric ratchet. The base form without ratchet is the standard SD perception smoothing equation (Sterman, 2000, Eq. 16-1, p.

610): $dP/dt = (A - P)/\tau$. This reflects the empirical finding that people respond to perceptions of conditions, not perfect real-time data (Stermann, 1989, p. 337).

The $\text{MAX}(0, \dots)$ operator enforces the Duesenberry (1949, Ch. 3, p. 32) ratchet: perceived income rises when actual exceeds it but freezes when actual falls. This is the asymmetric adjustment that Bernard and Taffesse (2014, Table 5, p. 150) document empirically: during the 2002–2004 Ethiopian drought, income fell 30% but aspirations fell only 5%. Kahneman and Tversky (1979) provide the mechanism: the loss aversion coefficient $\lambda \approx 2.25$ makes downward reference-point revision psychologically approximately twice as costly as the equivalent upward gain.

The ratchet is structurally essential to the Delayed Reward Trap. Without it, perceived income would fall when actual income falls, aspirations would adjust downward with it, the aspiration gap would remain manageable, and no trap would form. With the ratchet, perceived income is frozen at its peak; as actual income falls, the income/reference ratio drops, the aspiration gap widens, and the system enters the demotivating zone of the aspiration effect lookup.

Perception_delay = 0.25 years (quarterly), reflecting semi-remote rural information diffusion through weekly markets, social gatherings, and family networks.

Key citations:

Stermann (2000, Eq. 16-1, p. 610–611); Stermann (1989, p. 337); Duesenberry (1949, Ch. 3, p. 32); Kahneman and Tversky (1979, Eq. 3, p. 279); Bernard and Taffesse (2014, Table 5, p. 150).

A.2.6 Social Aspiration Level

Equation:

$$\text{Social_Aspiration_Level} = \text{INTEG}(\text{Aspiration_change}, 0.5)$$

$$\text{Aspiration_change} = \text{MAX}(0, (\text{Indicated_aspiration} - \text{Social_Aspiration_Level}) / \text{Perception_delay})$$

Initial value: 0.5 (dimensionless index; 50% of reference income ratio)

Social Aspiration Level is a stock because aspirations are history-dependent cognitive states that accumulate gradually through exposure and social comparison, not instantaneous responses to current conditions. Genicot and Ray (2017, Eq. 1, p. 494) formalise this as $a_{i,t+1} = G(a_{i,t}, y_{i,t}, \bar{y}_{i,t})$: future aspirations depend on current aspirations, not just current inputs. This history-dependence makes the stock formulation mandatory in SD.

The identical $\text{MAX}(0, \dots)$ ratchet applied to Perceived Income enforces Genicot and Ray's (2017, pp. 496–497) history-dependence condition: aspirations cannot fall below the peak level previously reached. Bernard and Taffesse (2014, Table 4, p. 147) confirm this empirically: the coefficient on lagged aspirations is 0.87 (highly significant) while the coefficient on income shocks is 0.03 (not significant). The ratchet is not an assumption but an empirically documented property of aspiration dynamics in rural development contexts.

The non-decrease assumption is the structural heart of the archetype. Without it, frustrated households would simply lower their aspirations, close the gap, and exit the trap. With it, aspirations persist at peak levels while income falls, the gap widens into the demotivating zone ($\text{gap} > r^* \approx 0.75$ per Table 5-1), and the system exhibits overshoot-and-collapse behaviour.

Key citations:

Genicot and Ray (2017, Eq. 1, p. 494, pp. 496–497); Bernard and Taffesse (2014, Tables 4–5, pp. 147–150); Duesenberry (1949); Kahneman and Tversky (1979); Ray (2006, p. 412); Appadurai (2004, p. 67).

A.2.7 Adaptive Capacity

Equation:

$$\begin{aligned}\text{Adaptive_Capacity} &= \text{INTEG}(\text{capacity_regeneration} - \text{capacity_erosion}, 1.0) \\ \text{capacity_erosion} &= 0.05 \times (1 - \text{Traditional_HH} / \text{Total_HH}) \times \text{Adaptive_Capacity} \\ \text{capacity_regeneration} &= 0.02 \times (\text{Traditional_HH} / \text{Total_HH})\end{aligned}$$

Initial value: 1.0 (full capacity; normalised dimensionless scale)

Adaptive Capacity is a stock representing the community's traditional ecological knowledge, seed diversity, inter-household risk-sharing arrangements, and coping practices. The erosion term formalizes Berkes and Turner's (2006, p. 485) finding that traditional ecological knowledge erodes in proportion to the abandonment of associated practices: $\text{erosion_rate} \times (1 - \text{Traditional_HH} / \text{Total_HH}) \times \text{Adaptive_Capacity}$. The proportional-to-stock structure produces standard exponential decay with a half-life of approximately 14 years under full specialisation.

The regeneration term ($0.02/\text{yr} \times \text{Traditional_HH} / \text{Total_HH}$) adds a recovery pathway representing deliberate knowledge-restoration efforts. The lower regeneration rate (40% of erosion rate) reflects the empirically documented asymmetry between knowledge loss and revival (Folke et al., 2010): traditional practices take generations to build, can be lost in one generation, but cannot be recovered at the same rate. The ratio $0.02/0.05 = 0.4$ captures this asymmetry.

$\text{Recovery capacity} = \text{Adaptive_Capacity} \times \text{Infrastructure_Resilience_Effect} \times \text{Traditional_Buffer_Effect}$, where $\text{Traditional_Buffer} = 0.2 + 0.8 \times (\text{Traditional_HH} / \text{Total_HH})$ preserves a floor of 0.2 at full specialisation. This multiplicative product is consistent with Meadows et al. (1972): resilience failure is determined by its most constraining dimension. Recovery capacity scales the denominator of the climate damage term, meaning declining adaptive capacity amplifies hazard damage non-linearly — the same event produces progressively larger income damage as the traditional livelihood base erodes (Gallopín, 2006).

Key citations:

Berkes and Turner (2006, p. 485); Folke et al. (2010); Walker et al. (2004); Gallopín (2006); Meadows et al. (1972); Sterman (2000, Eq. 10-2, p. 386).

A.3 Flows (9 Variables)

A.3.1 Transition Rate

Equation:

$$\text{Transition_Rate} = \text{Traditional_Livelihood_Households} \times \text{Fractional_Transition_Rate}$$

$$\text{Fractional_Transition_Rate} = \text{Baseline_rate} \times \text{Aspiration_effect} \times \text{Information_effect} \times \text{Resource_constraint} \times \text{Risk_perception_constraint}$$

The population-times-propensity structure directly implements Bass (1969, Eq. 1, p. 216) and Sterman (2000, Eq. 9-1, p. 332): $\text{Adoption_Rate} = \text{Potential_Adopters} \times \text{Adoption_Fraction}$. Traditional_HH = those who have not yet adopted (potential adopters).

$\text{Fractional_Transition_Rate}$ = probability of adoption per unit time.

The multiplicative formulation of the fractional rate implements Liebig's Law of the Minimum as applied to multi-constraint systems (Sterman, 2000, pp. 348–351): if any single factor reaches zero, the transition rate collapses to zero regardless of other factors. This is appropriate because all five factors are necessary (not substitutable): aspirations without information access produce no action; aspiration and information without resource adequacy produce no viable transition; and so on.

$\text{Baseline_rate} = 0.1/\text{yr}$ (10% of traditional households transition per year in unconstrained conditions). This is within the Rogers (1962) early-majority adoption range.

Key citations:

Bass (1969, Eq. 1, p. 216); Sterman (2000, Eq. 9-1, p. 332, pp. 348–351); Rogers (1962, Ch. 7); Liebig's Law as applied in Meadows et al. (1972).

A.3.2 Reverse Transition

Equation:

$$\text{Reverse_Transition} = \text{New_Livelihood_Households} \times \text{Baseline_reverse_rate} \times \text{Exit_pressure}$$

$$\text{Exit_pressure} = \text{MIN}(1, \text{MAX}(0, 1 - (\text{Perceived Income} / \text{Reference income}) / \text{Social Aspiration Level}))$$

Reverse transitions extend the standard Bass (1969) diffusion structure, which has no exit pathway. They are added to represent households exiting new livelihoods when income falls sufficiently below aspiration-weighted acceptable levels. Hirschman (1970, Ch. 1–2) establishes the theoretical basis: exit is available to actors in declining situations but requires overcoming switching costs and loss aversion (Kahneman and Tversky, 1979). The baseline reverse rate (0.02/yr) is 20% of the forward rate (0.1/yr), reflecting these costs.

Exit pressure activates when income falls below the aspiration-weighted acceptable minimum, implementing Genicot and Ray's (2017, Proposition 1, p. 503) aspiration failure threshold. The $\text{MAX}(0, \dots)$ prevents negative exit pressure (income exceeding aspirations should not create

reverse pressure). Exit pressure = 0 when income equals the critical threshold; = 1 when income = 0.

Key citations:

Hirschman (1970, Ch. 1–2); Genicot and Ray (2017, Proposition 1, p. 503); Kahneman and Tversky (1979); Sterman (2000, pp. 193–194).

A.3.3 Construction

Equation:

$$\text{Construction} = (\text{Total_Infrastructure_investment_expenditure} + \text{Transition_Rate} \times \text{Initial_infrastructure_fraction} \times \text{Average_Income_per_paying_HH}) / \text{Average_unit_infrastructure_cost}$$

Construction converts monetary investment into capacity units entering the enabling pipeline. Investment has two components: exogenous program expenditure and endogenous household reinvestment (income from transitions funds further infrastructure). This endogenous investment is the mechanism behind R2 (Infrastructure Investment loop): income growth funds infrastructure growth, which funds further income growth. The division by Average_unit_cost converts from currency to capacity units.

Key citations:

Lyneis and Ford (2007, Section 3.2); Sterman (2000, Ch. 11); Solow (1956) for capital accumulation structure.

A.3.4 Commissioning

Equation:

$$\begin{aligned} \text{Commissioning} &= \text{Infrastructure_Gap} / \text{Benefit_realization_delay} \\ \text{Infrastructure_Gap} &= \text{Enabling_Infrastructure} - \text{Functional_Infrastructure} \end{aligned}$$

Gap-driven commissioning creates an endogenous catch-up dynamic: when enabling exceeds functional, there is pressure to complete projects. Benefit_realization_delay = 2 years represents the average time from construction completion to operational commissioning (installation, testing, training). This gap-adjustment structure is the standard SD pipeline formulation (Sterman, 2000, pp. 422–424).

Key citations:

Sterman (2000, pp. 419–426, Eq. 11-7); Lyneis and Ford (2007, pp. 167–170).

A.3.5 Functional Depreciation

Equation:

$$\text{Functional_Depreciation} = \text{Functional_Infrastructure} / \text{Infrastructure_lifetime} + \text{Climate_infrastructure_destruction}$$

Two independent mechanisms: continuous wear-and-tear (10-year average lifetime per Sterman, 2000, Eq. 10-2) and discrete climate event destruction (documented in Herrera de Leon and Kopainsky, 2019). The addition is justified because the mechanisms are independent. Infrastructure_lifetime = 10 years is consistent with rural irrigation and small-scale energy infrastructure in mountain contexts.

Key citations:

Sterman (2000, Eq. 10-2, p. 386); Solow (1956, p. 66); Herrera de Leon and Kopainsky (2019).

A.3.6 Aspiration Change

Equation:

$$\text{Aspiration_change} = \text{MAX}(0, (\text{Indicated_aspiration} - \text{Social_Aspiration_Level}) / \text{Perception_delay})$$

Identical ratchet structure to income_perception_change (Section A.3.9). Aspirations adjust toward the indicated target with a delay but cannot fall below current level. See Stock A.2.6 for full theoretical justification. The shared Perception_delay parameter (0.25 years) means aspirations and perceived income adjust at the same pace, which is the conservative assumption; in practice aspiration adjustment may be slower than income perception.

Key citations:

Genicot and Ray (2017, Eq. 1, pp. 494, 496–497); Duesenberry (1949); Bernard and Taffesse (2014, Tables 4–5).

A.3.7 Income Perception Change

Equation:

$$\text{income_perception_change} = \text{MAX}(0, (\text{Mean_income_per_household} - \text{Perceived_Income}) / \text{Perception_delay})$$

See Stock A.2.5 for full theoretical derivation. The MAX(0, ...) implements the Duesenberry (1949) ratchet empirically validated by Bernard and Taffesse (2014). This is structurally the ninth flow in the model.

Key citations:

Sterman (2000, Eq. 16-1, p. 610); Duesenberry (1949, Ch. 3, p. 32); Sterman (1989, p. 337); Bernard and Taffesse (2014, Table 5, p. 150).

A.3.8 Capacity Erosion

Equation:

$$\text{capacity_erosion} = 0.05 \times (1 - \text{Traditional_HH} / \text{Total_HH}) \times \text{Adaptive_Capacity}$$

See Stock A.2.7 for full derivation. Erosion_rate = 0.05/yr (5% annual erosion of remaining capacity under full specialisation) consistent with Berkes and Turner (2006, p. 485).

Key citations:

Berkes and Turner (2006, p. 485); Folke et al. (2010); Sterman (2000, p. 386).

A.3.9 Capacity Regeneration

Equation:

$$\text{capacity_regeneration} = 0.02 \times (\text{Traditional_HH} / \text{Total_HH})$$

Regeneration rate = 0.02/yr represents active knowledge-revival pathways. The rate is calibrated to be less than the erosion rate (40%) to represent the documented asymmetry between knowledge loss and revival (Folke et al., 2010). Berkes (1999, Ch. 8) documents that traditional knowledge can be revitalised through deliberate educational programs and intergenerational transmission, but this process is substantially slower than erosion through abandonment.

Key citations:

Berkes and Turner (2006, p. 487); Folke et al. (2010); Berkes (1999, Ch. 8).

A.4 Key Auxiliary Variables

A.4.1 Climate Event Occurs

Equation:

$$\text{Climate_event_occurs} = \text{RANDOM_POISSON}(0, 100, \text{Hazard_frequency} \times \text{TIME_STEP}, 0, 1, \text{seed})$$

This implements a Poisson process (mean = Hazard_frequency × TIME_STEP events per simulation step) for discrete rare climate events, consistent with the Herrera de Leon and Kopainsky (2019) framework for rare-event modelling in agricultural systems.

Hazard_frequency = 0.3 events/year for the generic synthesis SFD. The scalar TIME_STEP variable of vensim is used to scale to the annual rate to the evaluation interval.

Key citations:

Herrera de Leon and Kopainsky (2019, pp. 287–309); Sterman (2000, Ch. 13, pp. 526–531).

A.4.2 Aspiration Effect (Lookup Table)

Equation:

$$\text{Aspiration_effect} = \text{WITH_LOOKUP}(\text{Aspiration_gap_ratio}, [\dots])$$

The lookup table implements an inverted-U (hill-shaped) relationship between aspiration gap and transition propensity, directly from Genicot and Ray (2017, Figure 2, p. 501, Proposition 2, p. 503). Genicot and Ray prove that under standard conditions, investment first rises and then falls

as a function of the aspiration gap, with maximum investment at a moderate gap. This is the structural basis for the Delayed Reward Trap's bifurcation: at moderate gaps the archetype amplifies transitions (R1 dominant); at large gaps it suppresses them and generates reverse transitions (B3 dominant).

Aspiration Gap Ratio	Effect
-5.0	0.05 Very satisfied — minimal motivation (complacency)
-2	0.1
-1	0.3
-0.2	0.8
0.0	1.0 Neutral — baseline motivation (no amplification)
0.2	1.35
0.4	1.55 (Peak) Moderate challenge — maximum motivation (stretch goal)
0.6	1.3
0.75 (r*) — interpolated	1.00 Motivating zone boundary — effect falls to unity
0.8	0.9
1	0.5 Aspiration failure zone — effort collapses by half
1.5	0.3
2	0.2
3	0.1
5.0	0.05 near-complete demotivated
10.0	0.01 Complete disengagement

The peak at gap ≈ 0.4 corresponds to Locke and Latham's (1990, Figure 2-1, p. 27) optimal goal difficulty, confirmed across 400+ studies. The decline at gap > 0.4 reflects Atkinson's (1957, Eq. 1, p. 360) achievement motivation theory: motivation peaks at intermediate difficulty ($P(\text{success}) \approx 0.5$). The near-zero effects at gap > 5 implement Seligman's (1972) learned helplessness: when success seems impossible, effort ceases.

The boundary $r^* \approx 0.75$ is the upper unity-crossing of the lookup (where `Aspiration_effect` returns to 1.0). By linear interpolation between the bracketing points (0.6, 1.30) and (0.8, 0.90): $r^* = 0.6 + (1.0 - 1.30) / (0.90 - 1.30) \times 0.2 = 0.75$. Above r^* , transition pressure is dampened below the baseline; above gap = 1.0, aspiration failure is active.

Key citations:

Genicot and Ray (2017, Figure 2, p. 501, Proposition 2, p. 503); Atkinson (1957, Eq. 1, p. 360); Locke and Latham (1990, Figure 2-1, p. 27, meta-analysis p. 29); Seligman (1972); Sterman (2000, pp. 348–351).

A.4.3 Indicated Aspiration

Equation:

$$\text{Indicated_aspiration} = (\text{Perceived_Income} / \text{Reference_income}) \times \text{Trend_multiplier} \times (1 + \text{FOMO_effect})$$

Three multiplicative drivers, each grounded independently:

1. Relative income position ($\text{Perceived_Income} / \text{Reference_income}$): Aspirations are relative, not absolute (Duesenberry, 1949, p. 32; Easterlin, 1974). The ratio compares own perceived income to a dynamic reference standard 15% above the better livelihood option:

$\text{Reference_income} = 1.15 \times \text{MAX}(\text{Average_new_income}, \text{Average_traditional_income})$. The 15% premium above the current best creates a persistent upward aspiration even when income is improving.

2. Trend multiplier = $1 + \text{Trend_sensitivity} \times \text{MAX}(0, \text{Smoothed_growth_rate})$: Households respond to income trajectory, not just level (Stermann, 2000, pp. 609–611; Kahneman, 2011, WYSIATI). Rising income raises the income target beyond current level. $\text{MAX}(0, \dots)$ creates asymmetric trend response: households extrapolate growth but not decline, consistent with optimism bias documented in Kahneman (2011, Ch. 24).

3. FOMO effect = $\text{FOMO_strength} \times (\text{New_HH} / \text{Total_HH})$: Social comparison pressure rises with adoption proportion. As more neighbours succeed, the pressure to match intensifies (Duesenberry, 1949; Frank, 1985; Genicot and Ray, 2017). At 50% adoption, $\text{FOMO_effect} = 0.20 \times 0.50 = 0.10$ (10% aspiration boost from peer pressure).

The multiplicative combination means all three forces compound: trend extrapolation amplifies the FOMO effect and vice versa. This is appropriate because the forces reinforce each other through common information channels (Stermann, 2000, pp. 348–351).

Key citations:

Duesenberry (1949, p. 32); Easterlin (1974); Genicot and Ray (2017, Eq. 1, p. 494); Frank (1985); Sterman (2000, pp. 609–611); Kahneman (2011, Ch. 24).

A.4.4 Information Effect

Equation:

$$\text{Information_effect} = (1 + \text{Social_Learning_Effect}) \times (1 - \text{Risk_Education_Effect})$$

$$\text{Social_Learning_Effect} = \text{Social_Learning_Strength} \times (\text{New_HH} / \text{Total_HH})$$

$$\text{Risk_Education_Effect} = \text{Risk_Education_Coverage} \times \text{Risk_Education_Strength} \times (\text{New_HH} / \text{Total_HH})$$

Information infrastructure is a bifurcating variable: it amplifies adoption through R3 (Social Learning) and dampens it through B6 (Risk Education), depending entirely on program content. The net effect is the product of both channels.

Social Learning Effect implements Bandura's (1977) observational learning: more adopters visible in the community → more success stories → higher adoption propensity. Effect = $1 +$ boost (multiplicative amplification above baseline).

Risk Education Effect implements the B6 dampening: deliberate risk communication reduces transition propensity. Effect = 1 – reduction (multiplicative below baseline).

At 30% B6 coverage and 50% adoption (New_HH = 500 of 1,000 total): Social_Learning_Effect = $0.3 \times 500/1000 = 0.15$; Risk_Education_Effect = $0.09 \times 500/1000 = 0.045$. Net = $(1 + 0.15) \times (1 - 0.045) = 1.098$. B6 dampens but does not override R3 at this coverage level.

Key citations:

Bandura (1977); Slovic (1987) for risk perception constraint; Sterman (2000, p. 150) for structural ambiguity at shared information node.

A.4.5 Infrastructure Productivity Effect

Equation:

$$\text{infrastructure_productivity_effect} = \text{MIN}(1, (\text{Functional_Infrastructure} / \text{MAX}(1, \text{New_HH})) / \text{Required_infrastructure_per_HH})$$

This implements the intensive-form production relationship from Solow (1956): output per worker is a function of capital per worker, $y = f(k)$. Productivity is proportional to functional infrastructure per household up to full adequacy ($k \geq \text{required}$), then flat (diminishing returns above requirements). MIN caps the effect at 1.0, representing the ceiling on productivity from infrastructure alone. MAX(1, New_HH) prevents division by zero when New_HH = 0.

The piecewise linear form (proportional below threshold, flat above) is a first-order approximation of the Inada conditions (Acemoglu, 2009, Ch. 2): marginal productivity is positive and diminishing, approaching zero as capital per worker becomes very large. The sharp cutoff at unity is a simplification; the qualitative trap behaviour is robust to smooth diminishing returns specifications.

Key citations:

Solow (1956, pp. 66, 70); Sterman (2000, pp. 348–351); Liebig's Law of the Minimum.

A.4.6 Macro Capacity Effect (Market Saturation)

Equation:

$$\begin{aligned} \text{Macro_capacity_effect} &= \text{WITH_LOOKUP}(\text{New_HH} / \text{Macro_Capacity_Limit}, [\dots]) \\ \text{Macro_Capacity_Limit} &= 500 + \text{DELAY3}(300, 1.33) \end{aligned}$$

The Macro Capacity Limit is not a static ceiling but expands dynamically: 500 base capacity plus a third-order delay on 300 additional capacity units, with a 1.33-year delay constant. This reflects lagged market development that partially relaxes the saturation constraint over the simulation horizon. Without this dynamic expansion, saturation would be a fixed wall at 500 households; with it, the market ceiling grows as infrastructure, supply chains, and institutional capacity develop, moderating the B5 saturation effect over time.

The lookup table shape (1.0 at zero utilisation, 0.9 at 0.8 utilisation, 0.5 at 1.0, 0.2 at 1.5) implements accelerating market saturation consistent with Cournot competition and logistic carrying-capacity models (Sterman, 2000, pp. 342–351). The sharp decline to 0.5 at full capacity (ratio = 1.0) is calibrated to generate the collapse behaviour documented in the reference modes; more gradual saturation would not produce the observed overshoot dynamics.

Key citations:

Sterman (2000, pp. 342–351, Ch. 9 'S-Shaped Growth'); Bass (1969); Meadows et al. (1972) on carrying capacity; Sterman (2000, Eq. 11-7) for the third-order delay structure.

A.4.7 Effective Vulnerability

Equation:

$$\text{Effective_vulnerability} = (\text{New_HH} \times \text{Vulnerability_new} + \text{Traditional_HH} \times \text{Vulnerability_traditional}) / \text{Total_HH}$$

Population-weighted average of livelihood-specific vulnerability coefficients. Generic synthesis SFD values: Vulnerability_new = 0.3, Vulnerability_traditional = 0.6, reflecting the empirical finding that subsistence livelihoods retain greater intrinsic climate buffering than commercialised alternatives (Gallopín, 2006; IPCC, 2022, Ch. 8). Case-specific values: Nepal vegetables 0.60, cereals 0.30 (observed drought sensitivity differential from FAO, n.d. and Karki, Mool, and Shrestha, 2010); Myanmar primary farming 1.00, secondary vocations 0.60 (derived from compound hazard profile of cyclones, flooding, and landslide risk in Shan State). The B4 polarity inversion across Nepal and Myanmar (Nepal: new > traditional vulnerability; Myanmar: new < traditional) generates the paper's second theoretical contribution.

Key citations:

Gallopín (2006); IPCC (2022, Ch. 8); FAO (n.d.); Karki, Mool, and Shrestha (2010).

A.5 Key Parameter Values

Parameter	Value	Units	Source / Justification
Total Household Population	1,000	Households	Reference community; Rogers (1962) diffusion model
Baseline transition rate	0.10	/year	Rogers (1962) early majority adoption range
Baseline reverse transition rate	0.02	/year	20% of forward rate; Hirschman (1970) switching costs
Perception delay	0.25	Years	Quarterly rural information diffusion; Sterman (1989)
Infrastructure lifetime	10	Years	Rural irrigation / small energy infrastructure; Sterman (2000) Eq. 10-2
Benefit realization delay	2	Years	Construction to operational commissioning lag

Erosion rate	0.05	1/year	Consistent with Berkes and Turner (2006)
Regeneration rate	0.02	1/year	40% of erosion rate; Folke et al. (2010) asymmetry
Hazard frequency (generic)	0.3	Events/year	1 event per 5 years average; Herrera de Leon & Kopainsky (2019)
Hazard frequency (Nepal)	0.3	Events/year	16 droughts 1972–2016; Karki et al. (2010)
Infrastructure damage fraction	0.20	Dimensionless	20% of functional stock destroyed per event
Base new livelihood income	150,000	Currency/HH/yr	Consistent with Nepal hill vegetable income range; Rai et al. (2019)
Base traditional income	67,000	Currency/HH/yr	Calibrated to Nepal cereal income baseline
Vulnerability: new (generic)	0.30	Dimensionless	Gallopín (2006); IPCC (2022)
Vulnerability: traditional (generic)	0.60	Dimensionless	Subsistence buffering capacity; Gallopín (2006)
Required infrastructure per HH	1.0	Units/HH	Normalised; to case study infrastructure deficits
FOMO strength	0.20	Dimensionless	Social comparison effect; Frank (1985); Genicot and Ray (2017)
Macro Capacity Limit (base)	500	Households	Market ceiling; calibrated to Shan State secondary vocation market
Macro Capacity expansion	300	Households	Dynamic expansion; Sterman (2000) third-order delay
Macro Capacity delay	1.33	Years	Market development lag; calibrated
Reference income multiplier	1.15	Dimensionless	15% above best livelihood; Duesenberry (1949)
Minimum acceptable income ratio	0.75	Dimensionless	Genicot and Ray (2017) aspiration failure threshold

Note: All parameter values are structurally derived or calibrated for qualitative behavioural plausibility. They are not empirically fitted constants. Specific numerical thresholds require validation against field monitoring data before operational deployment (Barlas, 1994).

A.6 Validation Approach

Given the theoretical character of the synthesis SFD, the appropriate validation mode is structural pattern matching rather than conventional goodness-of-fit testing (Barlas, 1994). Three criteria are applied:

1. Behaviour-over-time pattern matching: The synthesis SFD must reproduce the qualitative dynamic signatures observed across the three case SDMs — S-shaped growth, overshoot-and-collapse under capacity constraint, aspiration ratchet behaviour, and slower recovery than growth. All four patterns are generated by the model structure.

2. Extreme-condition testing (Sterman, 2000, p. 858): With Hazard_frequency = 0, the climate damage term vanishes and the system exhibits pure S-shaped growth. With Aspiration_change ratchet removed (allowing aspirations to fall), the trap does not form, confirming the ratchet is structurally necessary. With Infrastructure_lifetime $\rightarrow \infty$ (no depreciation), infrastructure accumulates without bound, removing the Latency Matching constraint and preventing overshoot.

3. Dimensional consistency: All equations are dimensionally consistent. Transition_Rate [HH/yr] = Traditional_HH [HH] $\times$ Fractional_Transition_Rate [/yr]. Climate_infrastructure_destruction [units/yr] = Climate_event_occurs [events/step] $\times$ Functional_Infrastructure [units] $\times$ damage_fraction [dimensionless] / 0.0078125 [yr/step].

Key citations:

Barlas (1994); Sterman (2000, pp. 858–892 on model testing); Richardson and Pugh (1981) on progressive structural testing.

A.7 References for Appendix

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