DOZER: a toy model of coastal hazard mitigation during a storm

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Abstract

Motivated by observations of emergency road-maintenance crews in coastal settings, DOZER is a video game in which the player uses a bulldozer to clear sand from a beachfront road during a storm. DOZER is also a toy model in a formal sense: a heuristic tool for insight into the dynamics of real-time intervention in the physical processes of a natural hazard. Here, I introduce DOZER as both a game and a numerical model, and demonstrate its utility for exploring conditions of divergence between a human-altered environmental system and its natural counterpart. I also situate the concept and mechanics of DOZER in the broader context of game design principles and philosophy. For models of systems in which adaptation is an important dynamic, ceding control of adaptive behaviours to a human player can enable novel model outcomes that random, probabilistic, deterministic, or genetic-programming approaches may not produce.

Keywords – agent-based model, rhetoric of failure, coastal hazard

1 Introduction

Some road crews plow snow; others plow sand. Beachfront roads are vulnerable to disruption from flooding and sediment deposition by coastal storms [1]. Tasked with maintaining the functionality of road networks as critical infrastructure, emergency road crews in low-lying coastal settings will use fleets of heavy machinery – front-end loaders, bulldozers, graders – to clear sediment washed or blown onto roadways [1, 2]. Crews may work intensively while a storm is in progress, plowing sediment back into the fronting dune even as water and sediment courses around their vehicles [3]. Such work constitutes a deliberate, enigmatic, and distinctly anthropic process of sediment transport [4]. Mechanised sediment transport during storm events remains unmeasured, and falls outside the scope of leading numerical models used to investigate, simulate, and predict physical change along low-lying coastal landscapes [3].

Plowing sand during a storm makes the intervention a synchronous morphodynamic process. Morphodynamics refers to changes in the physical landscape that develop as a function of feedbacks between fluid flow, topography, erosion, and deposition. Topography directs flow, which affects spatial patterns of erosion and deposition, which reshape topography, which redirects flow. Using a bulldozer to intervene in active storm-driven deposition means that the bulldozer and storm-driven flow become morphodynamically coupled: each affects, and is affected by, the pathways and patterns of flow and deposition shaped by the other. Modelling these dynamics are not limited by their physics. Rather, to model a bulldozer as an agent of morphodynamic change requires representing the behavioural agency of a bulldozer operator.

Here, I introduce DOZER, a single-player video game in which the player guides a bulldozer to plow sand getting washed onto a beachfront road **(Fig. 1)**. Although stylised as a retro arcade game, DOZER is also an exploratory numerical model of deliberate, synchronous intervention into storm-driven coastal processes. DOZER can be typified as a participatory agent-based model [5, 6], in which the mechanisms for adaptive agent behaviour are handled by a human user rather than through machine learning [7, 8]. I use ensemble model results from my own game play to show how DOZER functions both as a game and as a heuristic tool for dynamical insight. I also situate DOZER in the broader context of game design principles and philosophy, and speculate on the potential for applying this kind of modelling to other human-altered environmental systems in which adaptive behaviour is an important dynamic.

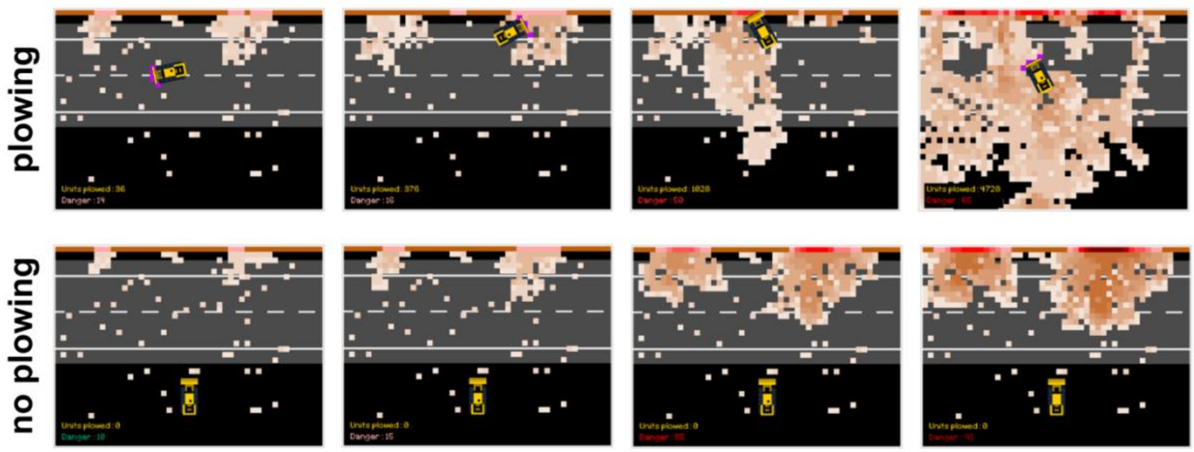

Figure 1. *Screenshots from DOZER. Upper time series shows DOZER plowing back pulses of storm-driven sand. Lower time series illustrates evolution of the game domain under the same forcing conditions without any intervention by the player.*

2 Method

2.1 Physical geographical context

The setting for DOZER is a sandy coastal barrier. Characterised by a shoreface, beach, dune crest, and back-barrier floodplain, coastal barriers are found all over the world. An essential mechanism by which barrier systems maintain their height and width relative to sea level is a process called overwash [9]. Typically triggered when water is pushed over the barrier during storms, overwash is a shallow cross-shore flow that transports sediment from the beach to the back-barrier floodplain. The sedimentary deposit that overwash leaves behind is called washover. Where washover deposition on a human-altered barrier is deliberately prevented or removed, theory suggests that with sea-level rise the barrier will tend to lose sediment volume over time, becoming more sensitive to storm impacts in the short term and possible drowning in the long term [3]. This tension between dependence upon and vulnerability to extreme weather is intrinsic to the persistence of human-altered barriers, and underpins the premise of DOZER.

2.2 Model design

Lazarus [10] details how the physical processes of overwash and washover are represented in DOZER. Here, I summarise the mechanics of the model that are most relevant to game play.

2.2.1 Domain – Discretised in a grid, the DOZER domain represents a plan-view reach of back-barrier floodplain. The beach is not modelled, nor is the landward edge of the floodplain. The dune is treated as a "one-line" slice in the alongshore dimension, visible to the player as a single row of coloured cells across the top of the domain. The shade of a cell occupied by sand conveys its relative volume: darker shades of brown represent deeper sand; empty cells are black. The model does not include any explicit dependence on grain size, but the version described here assumes a sandy barrier. A two-lane road spans the upper half of the domain, but is only aesthetic.

2.2.2 Overwash flow and washover deposition – DOZER draws on research indicating that overwash sites may organise into spatial patterns by competing with near neighbours for capture of forcing flow [11, 12]. In its initial state, the model has a fronting dune of uniform height alongshore, which overwash punches through. A game typically has three or four overwash sites, spaced at quasi-regular intervals along the dune, each associated with a proportion of flow capture. Overwash sites, their relative spacing, and their proportions of flow capture are determined by a subroutine using watersheds of directed random walks [10, 13].

Overwash is delivered from the top of the domain to the floodplain in pulses, which occur at randomised intervals every 3–10 seconds. Each pulse through an overwash site entrains sand, incrementally incising a channel through the fronting dune. Sand in the model is conserved: volume eroded from the dune is transferred to washover on the floodplain. Instead of solving hydrodynamics, the model uses a rule-based flow-routing routine to redistribute and deposit sand [2, 10]. Cumulative deposition evolves the floodplain condition, with each depositional pattern steering the next.

The top row of the screen reflects the relative integrity of the dune, serving as a kind of status bar. Reaches of dune that are intact (at or near their initial height) are a dark brown, indicative of maximum sand volume; the more deeply incised the dune is at a given cell, the redder that cell becomes. A "danger" meter at the bottom left of the domain shows the maximum incision along the dune (as a percentage of initial height). When overwash at a given site fully incises through the dune to the floodplain floor, the game ends.

2.2.3 Bulldozer agent – When the game begins, DOZER sits idle, centred in the bottom third of the screen. The player controls the actions of the bulldozer using keyboard inputs. The bulldozer can move forward or backward, and rotate in a full circle to the right or left. The player also determines whether the plow blade of the bulldozer is up or down. Player inputs are nonexclusive, so that the bulldozer can travel, turn, and plow simultaneously.

If the bulldozer is traveling forward with the blade down and encounters a sandy cell, the volume of sand at that cell is subtracted from the floodplain and added to the plow blade. The blade can collect and push sand up to a maximum volume (i.e., the blade capacity), beyond which the blade stays full but skims over the floodplain surface without picking up any more sand. Sand stays on the blade until the player deposits it by raising (releasing) the plow. The bulldozer cannot push sand off the edges of the domain.

The start screen provides instructions for how to operate DOZER, but the player is given no explicit directive or objective. There are no fixed rules of play for bulldozer operation.

2.2.4 Process coupling – Coupling between overwash flow, washover deposition, and DOZER actions (i.e., morphodynamic coupling) is affected in two ways. The first is expressed on the floodplain. By altering the shape of the washover deposits as they develop, plowing reorients local flow paths of steepest descent, diverting overwash flow and washover deposition into patterns different from those that would form in the absence of plowing. Floodplain coupling occurs as long as the player plows at least part of a washover deposit somewhere in the domain.

A second mode of coupling occurs if the player plows sand back into incised sections of the dune. Where partial infilling of the dune reduces or blocks subsequent overwash, forcing flow is redirected laterally and reapportioned to the nearest neighbouring overwash site (or sites). No new overwash sites are created during a game, but existing sites that DOZER closes can reactivate as the forcing flow gets redistributed. This effectively assumes that freshly infilled sections of the dune are structurally weaker. I refer to this second mode of coupling as "whack-a-mole" dynamics: plugging one incision exacerbates incision elsewhere along the fronting dune. Because the model assumes constant forcing, the storm-driven flow can be redirected but never fully stopped.

2.2.5 Dummy model for comparative analysis – During a game of DOZER, a dummy model of the overwash and washover routines, absent the player, runs in parallel. The dummy model is not visible to the player and does not affect game play, but enables direct quantitative comparison between human-altered versus natural outcomes given the same forcing conditions.

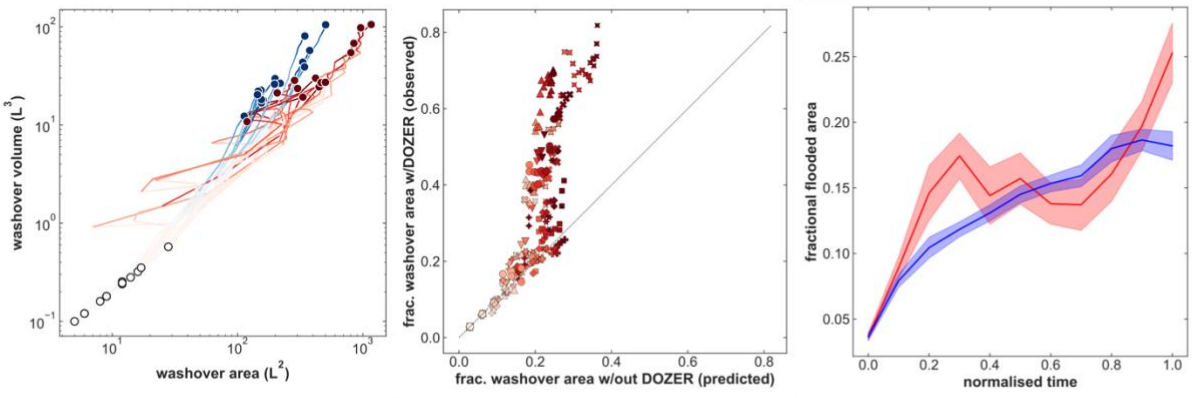

Figure 2. *Examples of analytics compiled from 10 games with different initial conditions.* ***(a)*** *Log-log plot of scaling relationship between washover volume and area for deposits with DOZER (red) versus the dummy model (blue). Open and closed circles show initial and final washover morphometry, respectively. Trajectories show transient states of allometric growth* [12]*; shade darkens with time elapsed.* ***(b)*** *Observed (DOZER) versus predicted (dummy) total washover area (as fraction of the floodplain); 1:1 reference line indicates perfect correspondence. Symbols denote different games.* ***(c)*** *Ensemble mean (±1 SE) of fractional flooded area versus normalised game time. Time series demonstrate impact escalation with DOZER intervention (red) relative to the dummy model (blue).*

3 Illustrative analytics

Even with its rule-based simplifications of physical processes, the numerical model on which DOZER operates yields washover deposits with geometric scaling relationships like those found in real settings and laboratory experiments [2, 11, 12, 14]. For example, washover volume changes as a function of area according to a power law **(Fig. 2a)**. The final geometric characteristics of the deposits, and the allometric trajectories they express as they grow [12], reflect power laws of different slopes for the dummy and DOZER conditions. In the dummy model, allometric growth of deposits reflects a smooth pattern of progressive expansion, while bulldozing affects excursive departures from the expected scaling.

Tracking state variables through time illustrates divergence between what is predicted by the dummy model versus observed in the DOZER condition **(Fig. 2b)**. Perfect correspondence between a variable predicted and observed falls on a 1:1 reference line. Although the dummy model and DOZER begin in perfect correspondence, their floodplain states soon diverge. Some variables reflect more pronounced divergence than others. For example, total depositional area exhibits an abrupt departure from predicted values, with DOZER trials resulting in approximately double the depositional area of the dummy model.

The game also produces a temporal pattern of impact escalation – a dynamical expression of divergence associated with human-altered systems prone to flooding [15, 16]. The basic form of the pattern is that interventions to limit frequent, minor hazard events unintentionally drive the human-altered system toward infrequent, major hazard events. In a real setting, this dynamic of escalation might develop over time scales of many decades or longer; here, DOZER compresses the dynamic within the time scale of a single storm **(Fig. 2c)**.

These signatures of divergence between natural and human-altered cases hold for ensembles of games with different initial conditions **(Fig. 2)** and for repeat trials of the same initial condition [10]. They are also a product of DOZER being both a numerical model and a game of responsive, adaptive behaviour.

4 Discussion

4.1 Failure as a premise

With a deliberate nod to classic arcade games like Space Invaders and Tetris, DOZER is unwinnable. The implicit objective – because the player is never given an explicit one – is the "goal of improvement" [17], or to play as long as possible before the game ends. At times, DOZER can feel winnable. When two successive pulses of overwash are separated by a long interval, a player might plow enough sand without interruption to stoke the illusory possibility of a winning state. Or a player may discover that plowing sand back into the dune extends the duration of a game – except doing so triggers the "whack-a-mole" dynamics that makes the dune deterioration both harder to anticipate and more catastrophic. DOZER thus employs a procedural "rhetoric of failure" [18]: no matter what the player chooses to do, or how technically skilled the player may be, failure is intrinsic, in that the game has no winning state. Its mechanics guarantee the inevitability of the conclusion.

4.2 Sources of uncertainty

Within this rhetoric, DOZER leverages five "sources of uncertainty" [19]. The most fundamental is *solver's uncertainty*. Each game has the same basic elements, but the puzzle of any given game – where to plow in order to sustain play for as long as possible – is different. Even when the configuration of the overwash sites is held fixed over repeated games by the same player, subtle differences in plowing actions means that no two floodplain puzzles are exactly the same [10].

Randomness is present in two mechanics of DOZER: the initial configuration of overwash sites at the start of a game, and the time interval between overwash pulses. Neither element is completely random. Over many games, overwash locations reflect a statistical distribution of preferred spacing alongshore, analogous to real settings [11, 12], but in any given game the player cannot know where in the dune the breaches will appear. Bounding the interval between successive overwash pulses (3–10 seconds) helps keeps the game from being metronomic, and from dragging. (A typical game of DOZER lasts just a few minutes.) Randomness in DOZER ensures that each game is different, but does not undercut the logics of game play [19].

Apart from randomness, *hidden information* is embedded in the volume of forcing flow directed through each overwash site. A player does not know *a priori* which overwash site will deliver the most washover, nor does the player get a clear sense of how plowing will affect pathways of overwash flow and washover deposition, or may redistribute forcing flow through the fronting dune.

Contending with this hidden information creates the mechanic of *analytic complexity* in DOZER. If the goal of the player is improvement [17], then analytic complexity comes in operating DOZER in a way that achieves the longest game. By diligently plugging a gap in the dune, the player may make their plowing task more unpredictable and harder. Following Costikyan [19, p. 86], the player has "only a handful of choices, but difficult ones", and is left "uncertain, even as they make a decision, that it is necessarily the correct decision to make".

Counterintuitively, the inevitability that DOZER will be overwhelmed is what sets up *narrative anticipation*. Costikyan [19, p. 95] notes that even when a narrative arc is a well-worn trope, "there is still great uncertainty on a moment-to-moment basis, and the…surprises...keep us interested". In DOZER, the player knows (after a few attempts) how the game will end, but not how or when the ending will arrive. Moment-to-moment narrative anticipation, driven by analytical complexity, builds "micro-tension" [20]: the longer a player postpones the inevitable in DOZER, the stronger the mechanics of uncertainty become.

4.3 DOZER as a persuasive game

The rhetoric of failure in DOZER is a contrivance of design, but unwinnability is what turns DOZER from a participatory agent-based model into a "persuasive" game [18, 21]. The extent to which this rhetoric of failure might translate to real settings [22] is left for the player to think about, or not: a player can drive DOZER unaware that the game derives from a real phenomenon [3]. In the wider context of climate-driven change on low-lying sandy coastlines, perhaps using bulldozers to intervene in storm impacts is discomfitingly analogous to holding on as long as possible before the game ends [22]. But DOZER itself does not take an explicit position or pass judgement on programmes of hazard intervention, and its meaning is left ambiguous: the player always fails, but can always play again. The role of failure, and of experimenting with failure, as opportunity for deep learning and critical thinking is a compelling dimension of game design [17, 23–26]. DOZER certainly can be used as a tool for teaching, learning, and engagement regarding adaptation to climate-driven hazards and management of environmental change [27–29]. However, DOZER is not oriented as "serious" in the sense that Abt [30, p. 9] employed: as a game with "an explicit and carefully thought-out educational purpose" or "created under the direct influence and guidance of external institutional goals" [18, p. 55]. Rather, DOZER is intended to be "persuasive" in the way that Bogost [18, p. 59] describes: as a game "whose promise lies in the possibility of using procedural rhetoric to support or challenge [emphasis original] our understanding of the way things in the world do or should work".

4.4 Style as reference

The aesthetic of DOZER as a retro arcade game is both a signifier of its nostalgic "indie-ness" [31], and a reference to a period in the 1980s and early 1990s when a wave of interdisciplinary research into nonlinear dynamics was leaning into grid-based models and cellular automata. Much of that work, back to its mainframe roots, became the corpus for models of complex adaptive systems [7, 8, 32]. Integrated throughout that corpus are games [21]. For example, Holland [7] recounts how at IBM in the early 1950s his then-labmate, Arthur Samuel, taught a prototype computer to play checkers [33]. Checkers, itself, was not the point: Samuel was using checkers as a simple, rule-based system to make inroads into machine learning.

That historical legacy is relevant to DOZER because representation of learning and adaptation remains a fundamental challenge in modelling agent systems [34. 35]. Ideally, the modeller establishes a minimal set of behavioural rules that give bounds to agent interactions but do not script them. One approach to enabling intelligent automata is to give them the mechanics of machine learning: an agent learns from and adapts to its environment (including other agents) by passing information through a genetic algorithm. An alternative approach, such as in DOZER, is to lend the model participatory mechanics [5, 6]. From there, the conceptual and procedural transformation from model to game is a step, not a leap [21, 36].

5 Future work

DOZER cannot capture why a player might choose to plow sand in one area versus another, but it can record where the player moved (and when and how much they plowed), providing at least a narrow window into player behaviour [10]. The rationale for a given strategy, if there is one, will be unknown without interviewing the player. DOZER could be used to explore how different players, and groups of players (e.g., naïve players, coastal experts, professional operators), engage with the same model condition, and what their actions collectively reveal about the emergence of strategy from moment-to-moment decisions. A multi-player format of DOZER could be used to examine the dynamics of cooperative strategies. Human players and a machine player could be tasked with a particular target for optimisation, and their approaches compared. For example, what is the most effective means of both keeping the road clear of sand and achieving the longest-possible run time? Do human and machine players converge on the same solution? The openness of the game to different strategies – regardless of what a given strategy achieves – may allow model outcomes that are otherwise inaccessible to random, probabilistic, deterministic, or even machine learning approaches to simulating adaptive behaviour. Extending the design premise of DOZER to examples of other human-altered environmental systems leaves ample room for dynamical surprises.

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Data availability – Game code, analytics, and a detailed model description are freely available at Lazarus [10].

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