ON THE EFFECT OF NEIGHBORHOOD SCHEMES AND CELL SHAPE ON THE BEHAVIOUR OF CELLULAR AUTOMATA APPLIED TO THE SIMULATION OF SUBMARINE GROUNDWATER DISCHARGE

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ABSTRACT

In order to design new search strategies for collaborating autonomous underwater vehicles, a novel simulator was developed to model the diffusion of groundwater discharge in shallow coastal waters. The simulation allows for the evaluation of new search strategies without running the risk of losing expensive hardware during the field testing.

The developed simulation is based on cellular automata. In order to reduce computational complexity, a novel two-dimensional cellular automaton with additional depth-information for each cell is used to simulate a three-dimensional nearshore environment.

The influence of different neighbourhoods and cell shapes on the behaviour of the cellular automaton is examined and discussed. Results show a faster rise of discharged fluorescent dissolved organic matter for hexagon cells. Also all examined neighbourhoods converge to a stable state after a finite number of iterations.

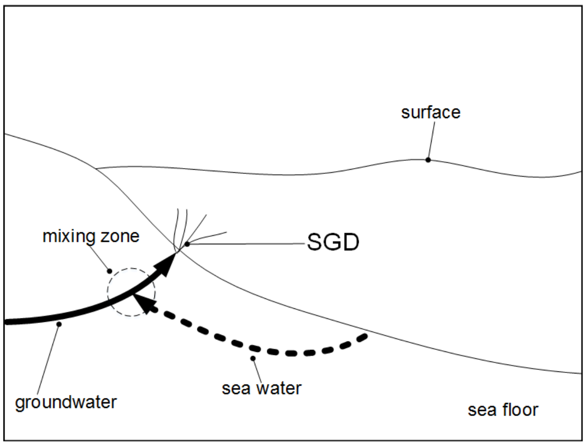
INTRODUCTION

The long term goal of this project is to develop a low cost and flexible environmental observatory, based on a swarm of autonomous underwater vehicles (AUV). AUVs can be used for the exploration of intermediate size areas and the precise measurement of parameters, for example oxygen, nutrients or Fluorescent Organic Matter (FDOM) (Zielinski et al. 2009). The interaction of the swarm should be managed by a search strategy, such as particle swarm optimisation (Nolle 2015). The search for submarine groundwater discharges (SGD) in coastal waters is one of the possible applications for such an observatory. Marine scientists are interested in locating and analysing these discharges because the nutrients discharged by SGD have a significant influence on the marine ecosystem (Dugan et al. 2010; Moore 2010; Nelson et al. 2015).

The area under investigation is a section of the north-western beach of the Spiekeroog island in the north-west of Germany. This area is in focus of many research groups because it represents a coastal transition zone at a barrier island with a freshwater lense (Röper et al. 2014; Beck et al. 2017). The model developed in this work simulates the three-dimensional environment using a two-dimensional cellular automaton.

Submarine Groundwater Discharge

Submarine groundwater discharge (SGD) consists of a flow of fresh groundwater and the recirculation of seawater from the sea floor to the coastal ocean (Moore 2010). The fresh water and the sea water discharges commingle in the so-called mixing zone (Figure 1) (Evans and Wilson 2016).



Figures 1: Submarine Groundwater Discharge of Fresh- and Recirculating-Water, modified after Evans and Wilson (2016)

The freshwater that flows to the ocean is a continuous and significant source of nutrients for the costal marine environment. Furthermore, the freshwater contains dissolved organic matter (DOM) (Nelson et al. 2015). The main source of this DOM is the dissolution of soil and terrestrial organic matter (Coble 2013). With a mass

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of approximately 700 Gt, DOM represents one of the largest organic carbon reservoirs on Earth, equalling the bio mass on land surface (Hedges 1992).

Coloured Dissolved Organic Matter

Coloured dissolved organic matter (CDOM) is the part of the DOM-pool that interacts with solar radiation (wavelengths 280 – 700 nm). The gain size of the particles is smaller than 0.2 - 0.4 µm (Nelson and Siegel 2013). CDOM have a major influence on the light distribution in sea water (Stedmon et al. 2010; Coble 2013).

A small part of the CDOM-pool is also fluorescent. This part is called fluorescent dissolved organic matter (FDOM). Fluorescent methods are used to analyse the chemical composition and the amount of DOM present in a sea water sample. The fluoresce of a sample is measured in quinine sulphate equivalent units (QSE). The QSE relates the intensity of FDOM to the fluoresce intensity of a standard compound (Kowalczuk et al. 2010).

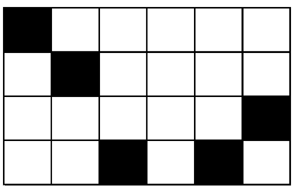
Optical methods are highly suitable for detecting spatio-temporal patterns of relevant biogeochemical parameters like dissolved organic matter or nutirents (Moore et al. 2009; Zielinski et al. 2011). In this work, the concentration of FDOM is modelled and simulated as described below.

SIMULATION

The simulation developed here is based on cellular automata (CA). This section introduces the basic concepts of CA and describes the main principles of the simulation developed. The rules used for the CA are introduced and an overview of different neighbourhood schemes is provided.

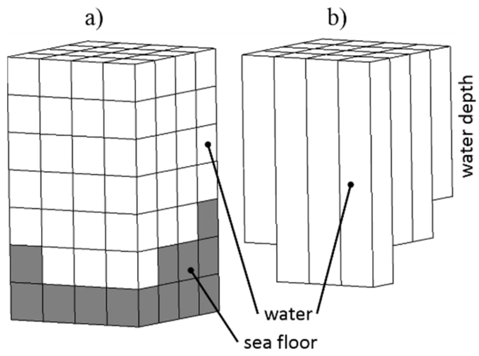
Cellular Automata

Cellular automata (CA) are mathematical models used for the simulation of complex systems. They consist of a finite collection of identical cells. Each cell has a current state, which is updated after one time step. The state of a cell in the next time step is based on its own current state and the current state of its neighbours. A CA discretizes a system in space and time (Wolfram 1984). Figure 2 shows an example of a two-dimensional cellular automaton with the dimensions 6 x 4. In the example, black cells are in state “true” and white cells are in state “false”.



Figures 2: Cellular Automaton of Size 6 x 4

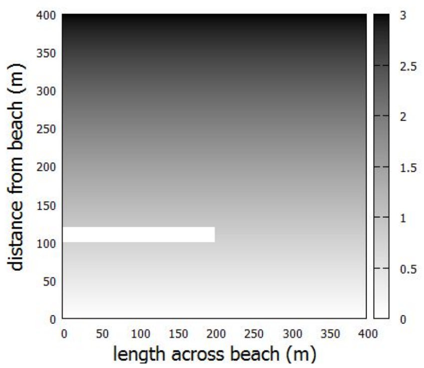
In principle, a three-dimensional model is needed to simulate the environment under investigation. However, due to the large amount of cells needed, this would be computationally expensive. Since the area to be simulated is very shallow and the water column is usually well mixed due to strong currents and waves in coastal waters (Röper et al. 2014), the simulation is based on a two-dimensional cellular automaton with additional depth-information for each cell (Figure 3). This reduces the number of cells significantly and therefore the computational effort needed. Figure 3a shows a three dimensional CA. It can be seen that the number of cells in the example is 112 including cells acting as boundaries (sea floor). In the two-dimensional representation (Figure 3b) on the other hand, only 16 cells are needed to model the same area.



Figures 3: Three-dimensional CA (left) and two-dimensional Representation (right)

The implemented simulation-environment covers an area of 400 m x 400 m. This area is divided into a number of symmetric cells. Each cell has an x- and a y-position as well as a depth and a FDOM level.

The depth increases from the beach (y-value = 0 m) to the open sea (y-value = 400 m) in steady steps. Furthermore, there is an obstacle (sandbank) with the depth of 0 m (Figure 4).



Figures 4: Depth-Profile of the Simulation Developed

The FDOM values in sea water are subject to wide variations (Kowalczuk et al. 2010). Therefore, in the simulation, seawater is assigned a FDOM level of one arbitrary unit, while the FDOM level of discharges was chosen to be 100 arbitrary units. Each cell is initialized with a FDOM-level of one unit.

To simulate the groundwater discharge two springs are added to the simulation. These springs have a volume flow rate of 0.125 m^3/iteration and a FDOM level of 100 units. The springs are located at position (100 m /200 m) and (200 m / 200 m). The left, right and top boundaries are located in the open sea. To simulate the exchange of water and nutrients with the open sea, cells located at this borders are acting as sinks. If a cell is a sink, it has a constant FDOM level of one unit. This ensures a steady flow of fresh seawater to the simulated environment and it prevents an enrichment of FDOM in the simulated environment.

Rules

The interaction of cells with their neighbours is based on a set of application specific rules. These rules define the dynamic behaviour of the model (Wolfram 1984; Nolle et al. 2016).

The developed CA is based on one simple rule only; the FDOM-value of a cell *x* at time step *t*+1 is calculated as the weighted average of the FDOM-values of the cell *x* and its neighbouring cells y_n and, if present, the FDOM-value of an existing spring at the position of the cell *x*. All values will be multiplied with the volume of the cells respectively with the volume flow rate of the spring. The sum will be divided by the sum of the volume of all cells in the neighbourhood. The rule is given in Equation (1), where *I* is representing the FDOM level in arbitrary units and *V* is representing the volume of the cells.

$$I_x^{t+1} = \frac{I_x^t * V_x^t + \sum\left(I_y^t * V_y^t\right) + I_s^t * V_s^t}{V_x^t + \sum\left(V_y^t\right) + V_s^t} \qquad (1)$$

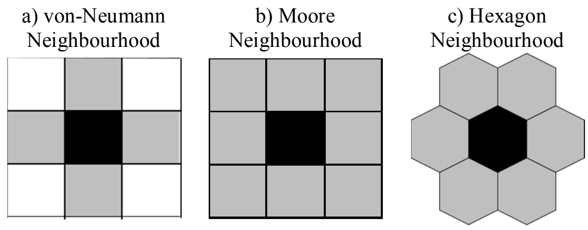
Where:
I_x^{t+1}: FDOM level in cell *x* in iteration *t+1*
I_x^t: FDOM level in cell *x* in iteration *t*
V_x^t: Volume of cell *x* in iteration *t*
I_y^t: FDOM level in neighbour cell y_n in iteration *t*
V_y^t: Volume of neighbour cell y_n in iteration *t*
I_S^t: FDOM level of spring located at cell *x* in iteration *t*
V_S^t: Volume flow of spring located at cell *x* in iteration *t*

In addition to the rules, the behaviour of a CA also depends on the chosen neighbourhood and cell shape.

Neighbourhoods and Cell Shapes Used

The most popular neighbourhoods are the von-Neumann neighbourhood (Figure 5a) and the Moore neighbourhood (Figure 5b) (Jiménez et al. 2005). Both are using square-shaped cells (Tzedakis et al. 2015).

In order to study the influence of the cell shape and neighbourhood on the behaviour of the CA, hexagon shaped cells (Figure 5c) (Gerhardt and Schuster 2012) are compared to square cells using the von-Neumann neighbourhood and the Moore neighbourhood.



Figures 5: Different Neighbourhood Definitions for two-dimensional Cellular Automata

Cells have defining properties, like size of the area covered or the length of the perimeter, which depend on each other. In the two-dimensional model developed here, the area size represents the volume of the cell whereas the length of the perimeter represents the surface area of the cell, through which it interacts with its neighbours. The ratio between area size and perimeter length depends on the shape of the cells. However, the ratio is different for square-shaped- and hexagon-shaped cells (Birch et al. 2007), i.e. they cannot be kept the same. In order to allow for a fair comparison of the different neighbourhood schemes, two hexagon-shaped automata are used in the experiments, one with the same area size as the square-shaped cells and one with the same perimeter length.

EXPERIMENTS

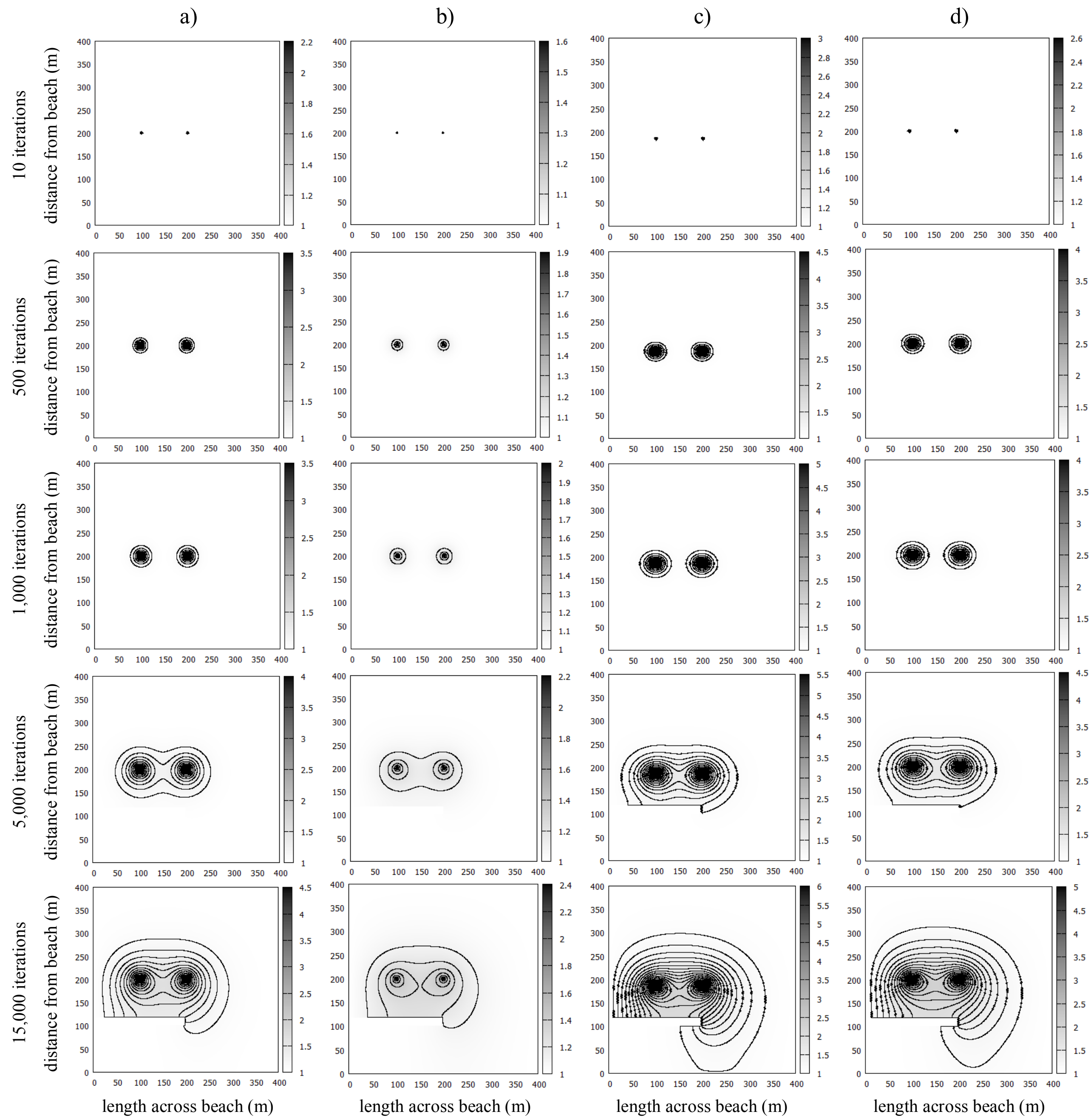
For the experiments, four different neighbourhoods were used, the von-Neumann neighbourhood, the Moore neighbourhood and two different versions of the hexagon neighbourhood. Each simulation was allowed to run for 15,000 iterations. The FDOM-level of each cell was logged for every iteration.

RESULTS

Figures 6a - d provide the FDOM-distributions after 10, 500, 1,000, 5,000 and 15,000 iterations for the different neighbourhoods used. The iso-lines show FDOM levels in steps of 0.1 units.

Each neighbourhood exhibits a dispersion of freshwater into the simulated costal area over the run time of the simulation. As expected, all neighbourhoods yield a symmetric distribution of FDOM around both springs. When the sandbank obstructs the distribution of FDOM it results in an asymmetric distribution of FDOM in the simulated area (Figure 6a - d).

At the beginning, the distribution of FDOM in both hexagon shaped neighbourhoods seems similar. Only when the sandbank obstructs the distribution the behaviour of the hexagon shaped neighbourhoods differ (Figure 6c and d).



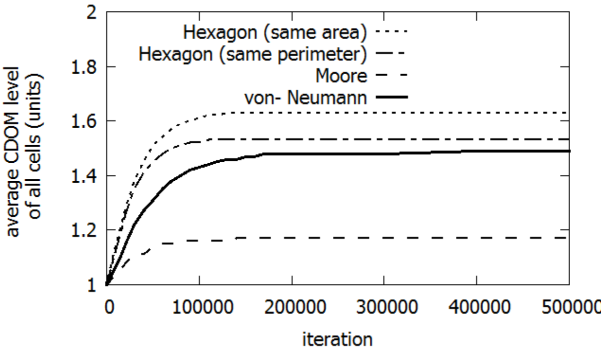
Figures 6: Distribution of FDOM over Time using the von-Neumann Neighbourhood (a), the Moore Neighbourhood (b), a Hexagon Neighbourhood with Same Area Size (c) and a Hexagon Neighbourhood with Same Perimeter Length (d)

Nearby the springs the FDOM level increases significant, while in all other areas the FDOM level increase only sparsely (Figure 6a - d). This behaviour agrees with the expected behaviour of small submarine groundwater discharges in coastal waters (Nelson et al. 2015).

The two springs represent a continuous inflow of FDOM units into the simulated area over the run. Because of that the average FDOM level for all cells has to increase over time. Although the FDOM input flow is the same for all four CAs, the development of the average FDOM levels differ (Figure 7) and hence, the neighbourhood schemes used have an influence of the distribution of FDOM in the area simulated.

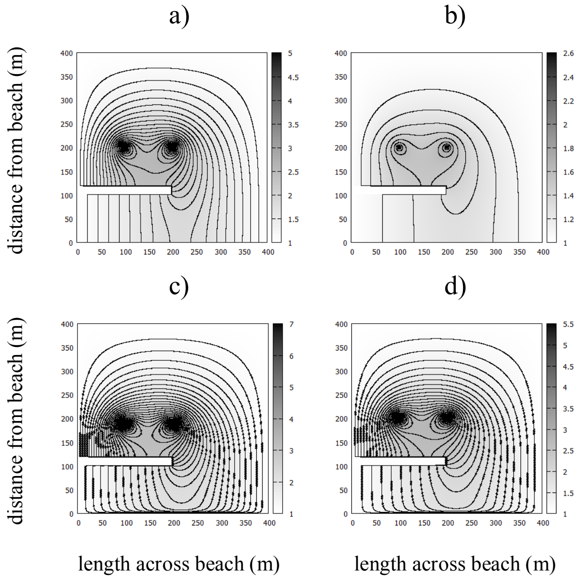
In such a state the amount of FDOM units supplied by the sources equals the amount of FDOM units that are lost on the boundaries of the CA. In this state the average of the FDOM level increase not anymore and the simulations converge towards stable states after a finite number of iterations.

To examine this behaviour of the different neighbourhoods, each simulation was run for 500,000 iterations. During the runs the average FDOM levels for all cells have been logged (Figure 7).



Figures 7: Convergence of Average FDOM level of all Cells for the Different Neighbourhoods

At the beginning the average increase fast for the hexagon shaped cells and the von-Neumann neighbourhood, while the average of the simulation using the Moore neighbourhood increase slower. However all used neighbourhoods converge to different stable states, i.e. the average value, the number of iterations and the appearance of the FDOM distribution (Figure 8) differ for the four used neighbourhoods.



Figures 8: Distribution of FDOM in the Stable State for the von Neumann (a)-, the Moore (b)-, the Hexagon-shaped same Area (c)- and the Hexagon-shaped same Perimeter (d)-neighbourhood

The convergence behaviour of the neighbourhoods using hexagon-shaped cells are similar (Figure 8c and d) while the behaviour of the neighbourhoods using square-shaped cells differ (Figure 8a and b). It can be observed that the FDOM level in the simulation using the von-Neumann neighbourhood expand much faster than that using the Moore neighbourhood (Figure 6 a and b).

Furthermore the average FDOM level in the stable state for the simulation using the von-Neumann neighbourhood is 1.49 units, while the average in the simulation using the Moore-neighbourhood is 1.17 units. However, the von-Neumann neighbourhood needs around 400,000 iterations to converge, while the Moore neighbourhood converges after around 140,000 iterations.

The parameter used to compare the hexagon shaped cells with the square shaped cells, i.e. either same area covered or same perimeter length, have an influence on the behaviour of the CA. While the simulation using hexagon shaped cells with the same area converges after around 130,000 iterations, the other simulation using hexagon shaped cells converges after around 110,000 iterations. A summary of these results is presented in Table 1.

Table 1: Convergence of Different Neighbourhoods

Neighbourhood	Iterations	Average
von-Neumann	400,000	1.49
Moore	140,000	1.17
Hexagon same Area	130,000	1.63
Hexagon same Perimeter	110,000	1.53

CONCLUSION AND FUTURE WORK

The aim of this research was to develop and determine a simulation based on cellular automata, which can be used for the evaluation of different search strategies for a swarm of autonomous underwater vehicles. The focus of this study was on the influence that different neighbourhoods might have on the behaviour of cellular automata. In order to reduce the computational effort, a novel two-dimensional CA was implemented that simulates a three-dimensional environment by treating depth, i.e. the third dimension, as a property of the cells.

From the experiments it can be seen that both, cell shape and neighbourhood affects the behaviour of the CAs. As depicted in Figure 7, the FDOM levels rise faster and the average level in stable state is higher for CAs with hexagon shaped cells. The behaviour of the simulations using hexagon shaped cells seems similar. It is estimated that the chosen parameters to compare the different cell shapes (i.e. area covered or perimeter length) have no significant influence on the behaviour of the CA (Figure 6c and d, Figure 8c and d).

In the next phase of this research it is proposed to use real FDOM measurements from the island of Spiekeroog to fine-tune the rule base of the Cellular Automaton and to incorporate waves and tides into the model.

The latter would allow for the simulation of additional transportation of water and FDOM between cells in the direction of waves. This will be realised by changing the volume of the cells periodically, with different amplitudes and frequencies for waves and tides. Also, some non-deterministic behaviour of the waves will be modelled and incorporated into the simulation.

This would then in turn allow for the cost-effective evaluation of different search strategies for swarms of autonomous underwater vehicles before such swarms are physically deployed to search for FDOM sources near the island of Spiekeroog.

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