

DDT chapter from the 1st edition of

Modeling the Environment

(included on the BWeb to supplement
Chapter 22 of the 2nd Edition)

Chapter 12. Simulating the Flow of DDT

System dynamics may be used to simulate the flow of material through the environment. The flows can involve multiple media such as water, soil, air and the bodies of animals and man. The models can help us understand the time delays between the application of a controlled flow and its arrival at “target” or “non target” organisms. The models are normally constructed in a step by step manner based on our understanding of material flows in each medium. The goal is to improve our instincts for managing the controlled flows to achieve the desired impacts on the target organism with minimal indirect effects on non target organisms. This chapter illustrates a general approach to simulating multi-media flows with an example of DDT. This pesticide is well known to students of the environment, and the example will reveal the usefulness of system dynamics in the field of toxicology. The ideas are useful wherever scientists wish to simulate material flows through several media (i.e., in pharmacokinetic modeling of drug flows in the body).

Figure 12.1 shows a flow diagram of a system dynamics model constructed by Jorgen Randers (1973) to study the long time delays between the application of DDT on crops and the appearance of the chemical in fish. The flow diagram follows the dynamo conventions explained in Appendix D. The DDT model is thoroughly documented in the DDT chapter published in *Toward Global Equilibrium*. You may work with the model directly in Dynamo, or you could choose to convert the model into any of the stock and flow programs. This chapter explains the DDT model in a step by step manner using progressively more complicated Stella models. By the end of the exercise, you will appreciate the applicability of system dynamics modeling to simulating material flows through multiple media. You will also appreciate some of the challenges that may arise when simulating material flows with a wide disparity in time constants.

Background

The birth of the modern environmental movement is often associated with the publication of Rachael Carson's *Silent Spring* in 1962. Carson described the dangerous side effects of chemicals invented during the 1940s and 1950s, including the insecticide Dichloro-diphenyl-trichloro-ethane or DDT.

DDT is an organic compound, one of the chlorinated hydrocarbons. It is toxic to insects but not to crops. DDT is extremely stable, and a single application remains toxic to insects for a long time. It was first put to use in the 1940s with spectacular success, and it was thought to be an ideal insecticide. Botkin and Keller (1995, p. 208) comment that scientists of that time thought they had finally "found the 'magic bullet' -- a chemical that rapidly seeks out individuals of a particular species and kills them, with no effect on any other form of life." It has been estimated that DDT and other insecticides have prevented the premature deaths of at least 7 million people from insect transmitted diseases such as malaria (Miller 1997, p. 382) In 1948, Paul Mueller received the Nobel Prize for his work on DDT. Carson's book appeared 14 years later to warn us of the dangers of continued use of DDT. She argued that insecticides and other pollutants were causing declines in many non target organisms.

DDT presents special problems because of its highly solubility in fat. DDT becomes stored in animal fat and is subject to bioconcentration as it moves up the food chain. Miller (1997, p. 385) gives an example from an estuary near Long Island Sound. DDT measurements in the water were around 2.5 parts per trillion. DDT moves to the zooplankton and into the small fish (minnows) where its concentration was measured at 0.5 parts per million. The larger fish eat the minnows and the ospreys eat the larger fish. The DDT concentration in the ospreys was measured at 25 parts per million, around ten million times larger than in the water.

DDT is especially dangerous to top carnivores such as ospreys, hawks, eagles, pelicans and the peregrine falcon. It disrupts hormone regulation of calcium levels causing thin eggshells and reproductive failure. The peregrine falcon, for example, has been on the endangered species (up until 1994) due to reproductive failure largely associated with DDT. These concerns led most developed nations to ban the use of DDT. It was banned in the United States in 1971, 9 years after the publication of *Silent Spring*. Since that time, there has been a dramatic recovery of some bird populations such as the brown pelican on the California coast (Botkin and Keller 1995, p. 208). DDT is still used today despite its impact on bird populations (and despite its declining effectiveness against insects). The UN World Health Organization reports worldwide usage at more than 30,000 metric tons per year.

A First Order Model of DDT Accumulation

Let's work toward a systems model of DDT flows in a step by step manner, beginning with some simple examples using the approach from Chapter 10. Figure 12.1 shows a model to simulate the accumulation of DDT in the soil. The inflow is *DDT applied to soil*; the single outflow is the degradation of DDT to harmless form. This occurs through chemical decomposition, photodecomposition and biological metabolism.

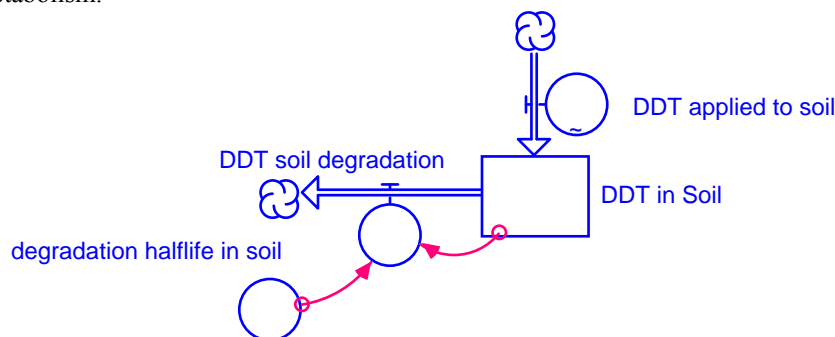


Figure 12.2. A simple model to simulate DDT in the soil.

This complex processes is represented by exponential decay with the *degradation half-life in soil* as the controlling parameter. Randers believes that this parameter can range from 3 years to 30 years; he recommends a “base case” estimate of 10 years based on tests by Nash and Woolson (1967) in which the effect of degradation was measured separately from other effects such as evaporation.

Recall from Chapter 10 that the equation for material flows with a half life parameter employ a 1.44 conversion factor to obtain the equivalent value of the time interval that the material remains in the stock. Since Randers was working with such highly uncertain estimates, he took the liberty of using 1.5 as a conversion factor. Let’s follow his example so that our results may be compared to his original results. Using Randers’ approximation, the equation for the outflow in Figure 12.2 would be written as:

$$\square \quad \text{DDT_soil_degradation} = \text{DDT_in_Soil} / (1.5 * \text{degradation_halflife_in_soil})$$

Figure 12.3 shows the simulated response of DDT in soil if 100 tons of DDT is applied to the soil in the year 1950. The accumulated amount jumps immediately to 100 tons and then declines in exponential fashion. Ten years after the application, around 50 tons would remain in the soil; after twenty years, around 25 tons would still remain.

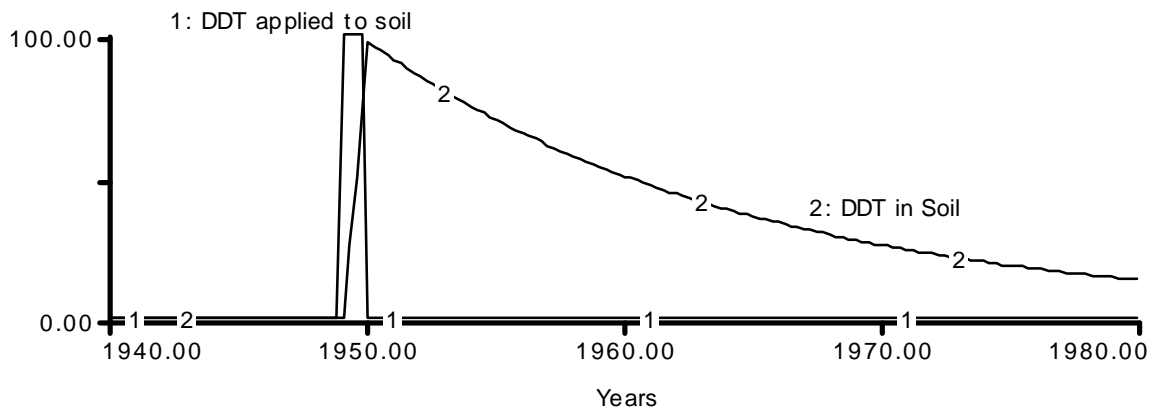


Figure 12.3. Simulated response of the first order model.

Figure 12.4 expands the simple model to include two additional outflows. The *DDT evaporation from soil* is controlled by *the evaporation half-life in soil* which may be set to 2 years. The third outflow represents the removal of DDT as the soil particles are swept away by water erosion. The DDT molecule is only slightly soluble in water, so it is not likely to go into solution. But DDT adheres strongly to soil particles, and these particles may be “washed away” by water erosion. Very little of DDT leaves the soil by this pathway, so Randers sets the *solution half-life in soil* at 500 years.

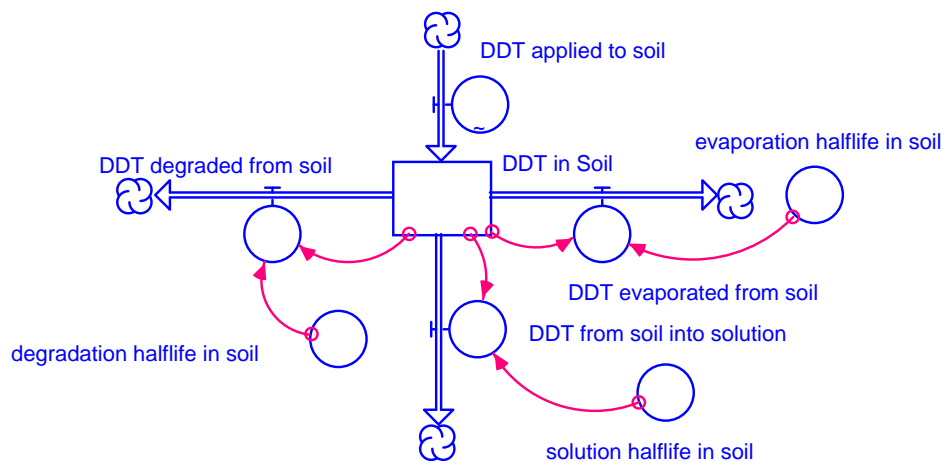


Figure 12.4. Expanding the simple model.

The simulated response of DDT in soil if 100 tons of DDT is applied to the soil in the year 1950 is shown in Figure 12.5. The accumulated amount jumps immediately, but it does not reach 100 tons because evaporation quickly goes to work removing some of the DDT from the soil. This new model suggests that very little DDT would be left in the soil after ten years.

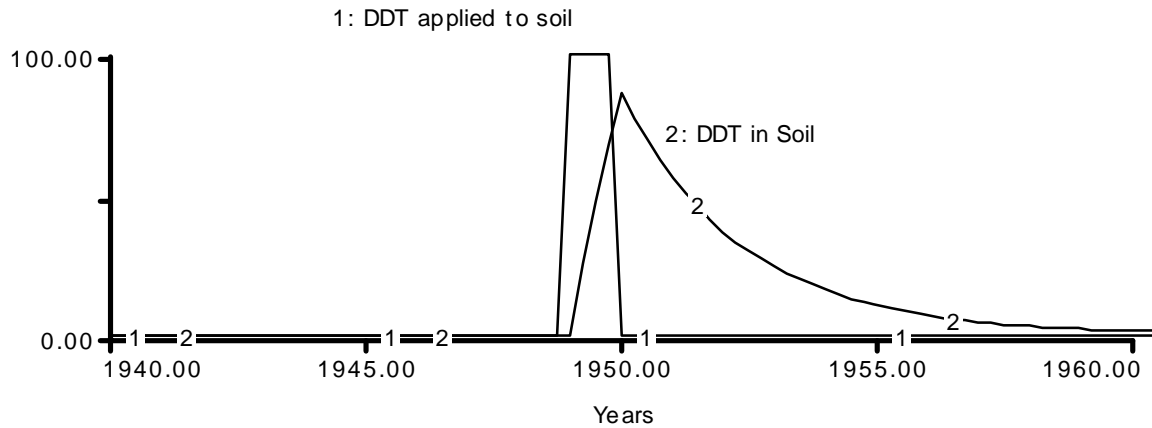


Figure 12.5. Simulated response of the expanded model.

A Second Order Model

At this point, you are probably thinking about the fate of the DDT that leaves the soil through evaporation. Once the DDT molecules are in the air, they become highly mobile and can move great distances before they fall to the ground again, mainly through precipitation. If it rains every two to three weeks, we might assume that DDT will quite quickly leave the atmosphere. But during the time it is airborne, it might be swept out over the ocean. Figure 12.6 shows a further expansion of the model to keep track of the airborne DDT and the amount of DDT returning to the soil due to precipitation. This is a second order model since it uses two stocks to keep track of the accumulation of DDT in the system.

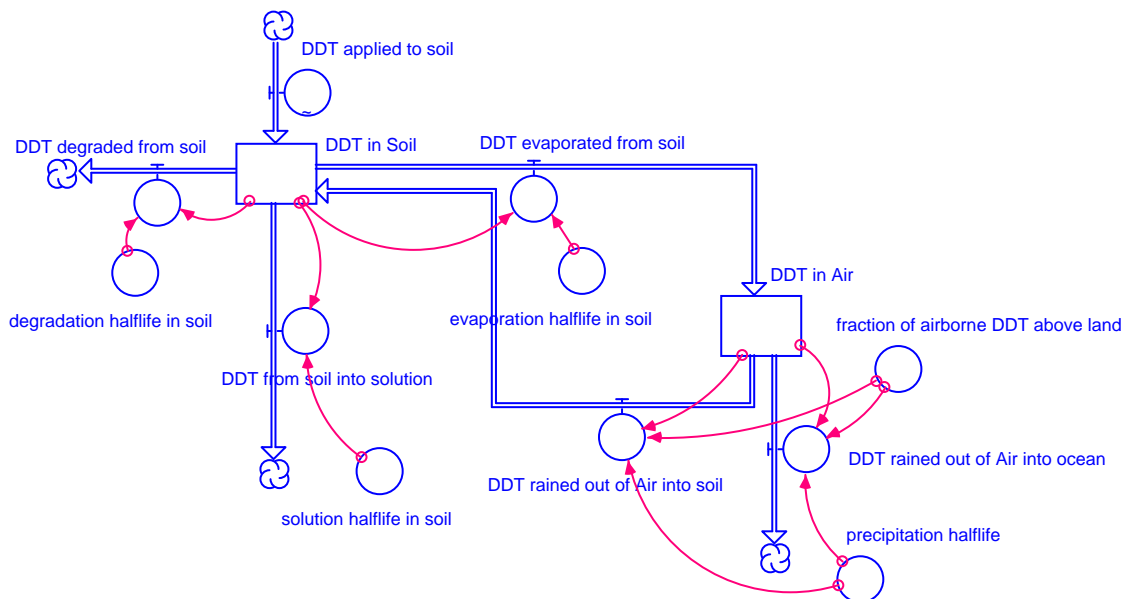


Figure 12.6. A second order model of DDT accumulation.

Following Randers' recommendations, the *fraction of airborne DDT above land* is set to 30%. The *precipitation half-life* is set to 0.05 years on the assumption that half of the airborne DDT is removed from

the atmosphere by precipitation roughly every 2-3 weeks. The simulated response of the new model is shown in Figure 12.7. As before, 100 tons of DDT is applied to the soil in the year 1950. The new model responds in generally the same manner as the previous model because of the rapid removal of DDT from the soil by evaporation. But the quick return of some of the airborne DDT to the soil causes a somewhat slower pattern of decline in Figure 12.7.

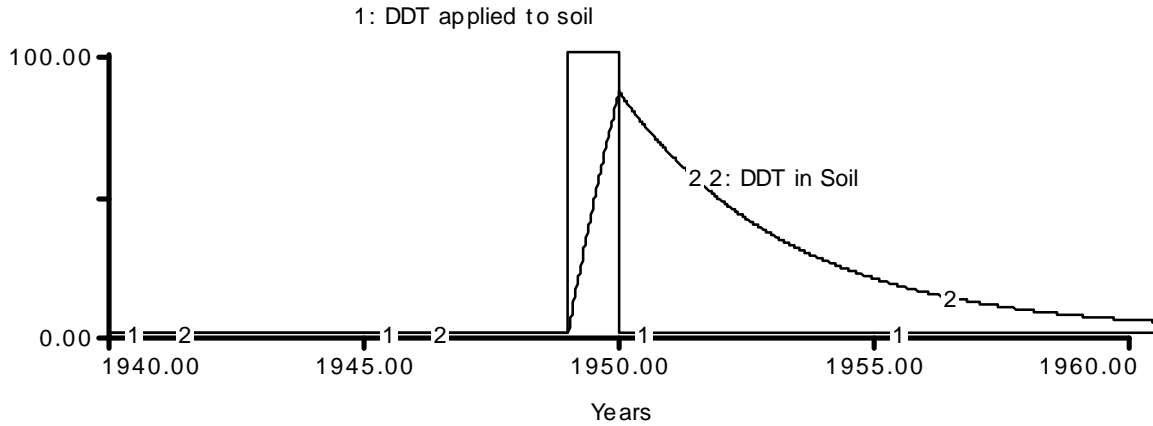


Figure 12.7. Simulated response of the second order model.

Now, let's expand the second order model to account for the possibility that some of the DDT becomes airborne immediately during its application. *Total DDT application* is now a converter, and the *airborne fraction* is used to split the applied DDT into two flows, as shown in Figure 12.8. The airborne fraction is set to 50% based on Randers' recommendation.

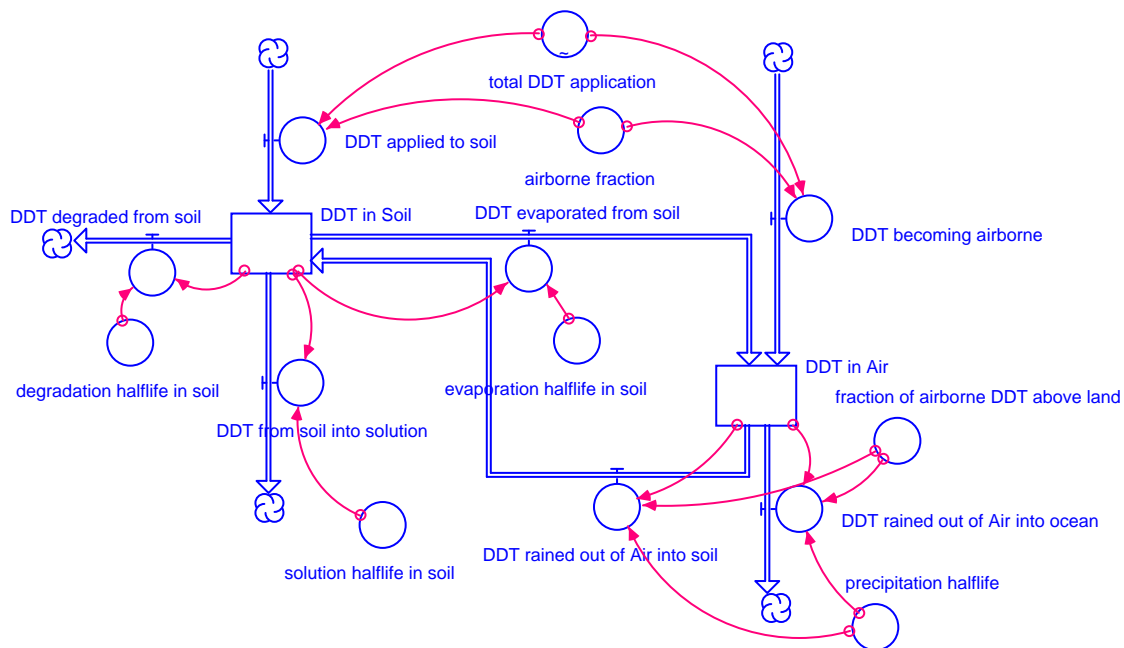


Figure 12.8. Expanding the second order model.

The simulated response of the new model is shown in Figure 12.9. The 100 tons of DDT in 1950 is now split into two flows. Half lands in the soil; the other half becomes airborne, where a fraction can return to the soil by precipitation. The simulated response shows that there would be very little DDT left in the soil ten years after its application.

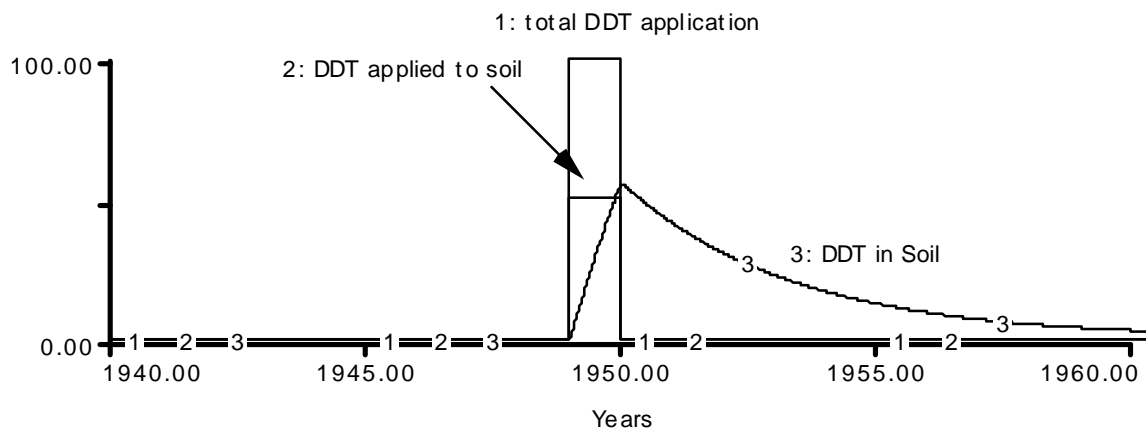


Figure 12.9. Simulated response with DDT inflows split between soil and air.

Randers' Model

The previous four models demonstrate how one may gradually build up a comprehensive simulation of the paths that DDT could follow through the environment. This approach may be continued to arrive at DDT concentrations in the ocean and in the fish. The fish concentration is especially important because the DDT becomes concentrated in the fish, and the fish are a source of food for many of the birds that experienced reproductive failure.

Figure 12.10 shows a flow diagram of Randers' original model. Five stocks are used to keep track of the DDT accumulation in the system. Each stock is measured in metric tons of DDT; each flow is measured in metric tons/year. Many of the flows use the term "rate" (i.e., *degradation rate in soil*). A "rate" variable in Dynamo corresponds to a "flow" variable in Stella, so don't be confused about their units. Each and every flow is measured in metric tons/year.

The top portion of Figure 12.10 is similar to the model in Figure 12.8. DDT enters the system at the top and works its way through two stocks. The pathway to the ocean is either through runoff from DDT in the rivers or by precipitation of airborne DDT that has drifted over the ocean. The lower portion of Figure 12.10 assigns one stock to keep track of DDT in the ocean and a second for DDT stored in fish. The concentration of DDT in the ocean is based on the mass of water in the mixed layer. The model uses an *ocean-plankton concentration factor* to estimate the concentration in plankton. (McKinney and Schoch (1998) explain the use of "bioconcentration factors (BCF) for pollutants that move up the food chain.) The concentration of DDT in plankton is then used to estimate the DDT update in fish. Randers gives "best estimates" and a range of uncertainty for each parameter based on a wide variety of information sources available in the early 1970s. His best estimates for the eight half-lives are as follows:

degradation half-life in soil	10 years
evaporation half-life in soil	2 years
solution half-life	500 years
precipitation half-life	0.05 years
run off half-life	0.1 years
degradation half-life in ocean	15 years
half-life of fish	3 years
excretion half-life from fish	0.3 years

Step Test and Equilibrium Diagram

Figure 12.11 shows results of a simple test with the application rate fixed at zero until the year 1950. Then DDT use increases abruptly to 100,000 metric tons/year and remains at the value for the rest of the simulation. The purpose of this “step test” is allow us to study the responsiveness of the model under simple conditions. The simulated response reveals that DDT in the soil would reach an equilibrium value within the first 10-15 years. This suggests that the “top part” of the model acts rather quickly to reach equilibrium. DDT in the fish, on the other hand, continues to grow decade after decade. It reaches around 300 metric tons and is still increasing at the end of the simulation.

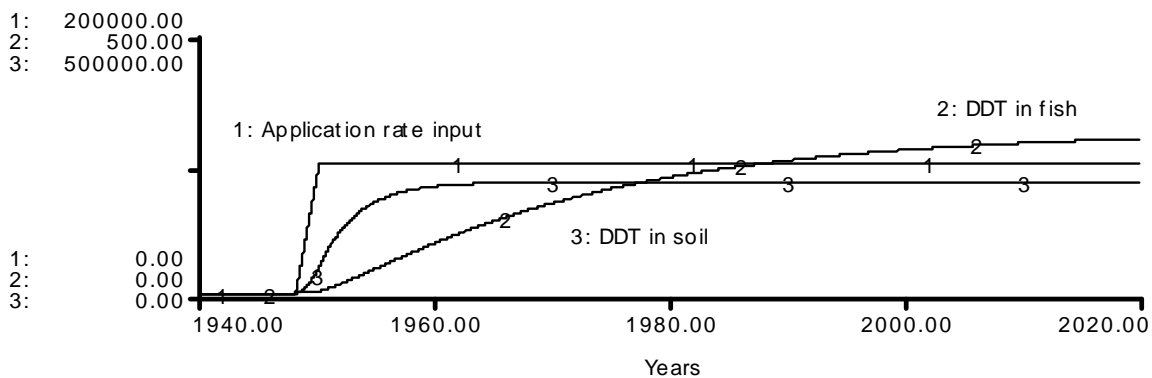


Figure 12.11. “Step test” of Randers’ model.

An equilibrium diagram based on the results at the conclusion of the step test is shown in Figure 12.12. The diagram focuses on the “top” portion of the model since this is the portion of the model that reaches equilibrium. It shows 100,000 metric tons/year entering the system from the application of DDT. The bottom of the diagram shows the two flows that move DDT into the ocean. One flow is the runoff from rivers. It accounts for only 288 tons/year. The second flow is precipitation of the airborne DDT. It accounts for over 85,000 tons/year of DDT flowing into the ocean. The numerical results in Figure 12.12 indicate that roughly 85% of the applied DDT will enter the ocean, almost entirely via precipitation that removes airborne DDT drifting over the ocean. Now, what about the other 15%? It appears to be leaving the system primarily through the degradation of DDT in the soil.

Suppose we were to cut DDT use to zero in the year 2021. You know that the flow of DDT into the ocean would not drop immediately to zero. There is a “backlog” of DDT built up in the soil, in the air and in the rivers. It will take time for this backlog to gradually work its way to the ocean. The total DDT stored in the system in the year 2020 is around 255,000 tons, and the vast majority is stored in the soil. You might expect that around 85% of the backlog would eventually work its way to the ocean, primarily via evaporation to the air and then through precipitation into the ocean.

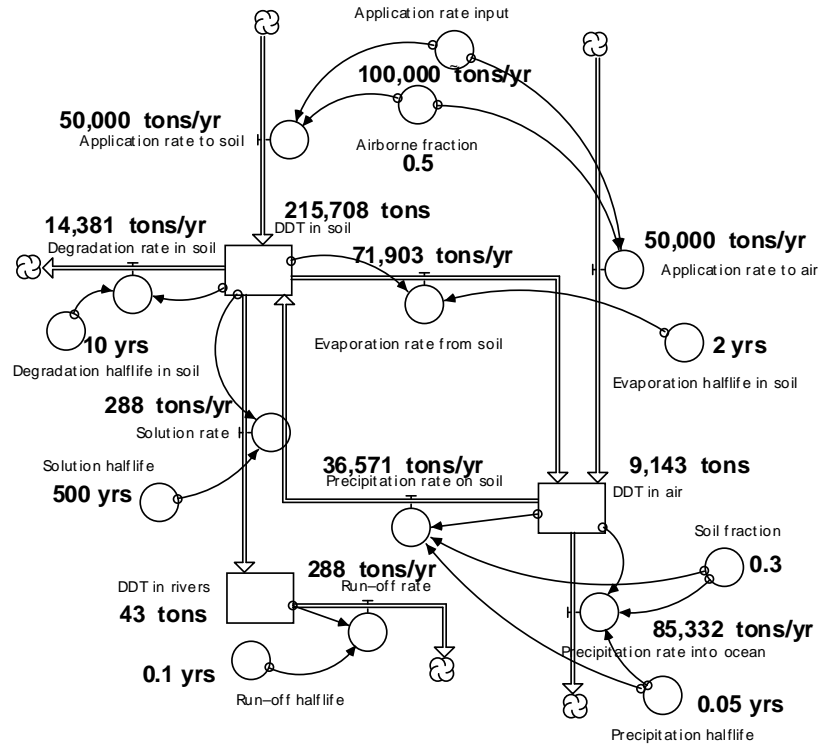


Figure 12.12. Equilibrium diagram for the “top” portion of the DDT model.

Implications of the Base Case Projection

Figure 12.13 shows Randers’ projection of DDT in the soil and in the fish if the application of DDT follows a “best estimate” scenario. It allowed for an increase in DDT use during the 1960s with a peak of around 175,000 tons/year during the 1970s. He reasoned that concern over the adverse impacts would cause a gradual phase out of DDT use by the year 1998. Figure 12.13 shows that the DDT in the soil would peak shortly after the peak use of DDT as a pesticide. DDT in the fish would continue to grow for several years, reaching a peak in the

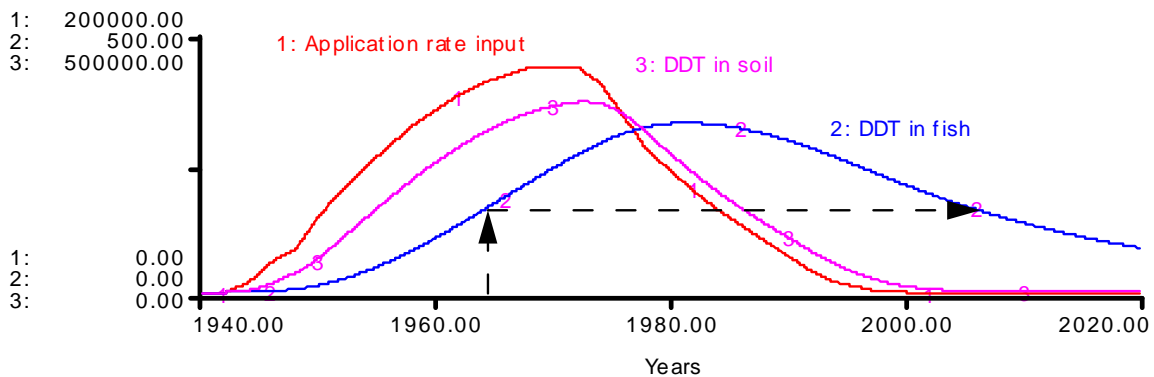


Figure 12.13. Base case results from Randers’ model.

1980s. The dashed lines in Figure 12.13 are included to draw your eye to the year 1962 when *Silent Spring* was published. The first arrow shows the level of DDT in the fish around 1962, a level sufficiently dangerous to trigger the publication of *Silent Spring*. Now follow the horizontal line to see how long one must wait for the simulated level of DDT in the fish to return to the 1962 value. The simulation reveals

that we must be prepared to wait around 50 years for the DDT to return to the level that first triggered the publication of *Silent Spring*.

Understanding this long delay in the transmission of a persistent pollutant was the main point of Randers' investigation. He used numerous simulations with variations in the uncertain parameters and with changes in the scenario for DDT use in the future. His findings might be summarized relative to the "fifty year return interval" in Figure 12.13. For example, with consistently optimistic estimates of all the uncertain parameters, the simulation required around 40 years to return to the 1962 level. In a scenario with a complete ban on DDT use around the world in 1971, 35 years would be required to return to the 1962 level. This long time interval reveals the considerable momentum associated with the flows of DDT through multiple media.

An Alternative Model

The numerical step size in Randers' model is set to 0.02 years, so 4,000 iterations are required to simulate the 80 year interval. The model clearly violates the "1,000 steps" guideline from Chapter 11. The guideline should challenge us to reconsider the long time horizon or reconsider the selection of such a small DT. Randers needed an 80 year time horizon to allow sufficient time to simulate the slow build up and slow decline of DDT in the fish. If we shorten the time horizon, we miss the main point of his exercise. So let's turn our attention to DT. The short DT is required because of the extremely short time constants such as the precipitation half-life and the run off half life. At 0.05 years, the precipitation half-life is the shortest time constant in the model. You know that we must set DT to less than half the shortest time constant, so the value of 0.02 years appears reasonable.

Perhaps we could revise the model if we were to eliminate this short time constant. But we have to be careful because we have learned from Figure 12.12 that precipitation of airborne DDT over the ocean is the principal pathway for DDT to reach the ocean. The revised model must maintain the pathway to the ocean, but perhaps we can eliminate the use of the stock to keep track of the amount of airborne DDT. (Eliminating this stock is similar to eliminating the stock assigned to the infant population in Chapter 11.)

The next shortest time constant is the runoff half-life which is set to 0.1 years. To eliminate this short time constant, we would need to eliminate the stock assigned to DDT in the rivers. The equilibrium conditions in Figure 12.12 indicate that we could eliminate this stock. Moreover, we would eliminate the pathway since only a minuscule fraction of the DDT makes its way to the ocean via the rivers.

Figure 12.14 shows a revised DDT model. The new model uses three stocks instead of five. It ignores the stock of DDT in the rivers, and it ignores the pathway through the rivers. The new model does not assign a separate stock to keep track of the airborne DDT. But it preserves in mathematical form the key path way that moves DDT to the air and into the ocean via precipitation. Figure 12.14 shows three clouds clustered in the upper right corner. One of these is a sink. It represents where DDT goes when it evaporates from the soil. The other two clouds are sources. They are drawn adjacent to the sink to convey the point that the model will not lose track (mathematically) of the DDT that evaporates from the soil. One portion of it goes right back into the soil; the remainder goes into the ocean.

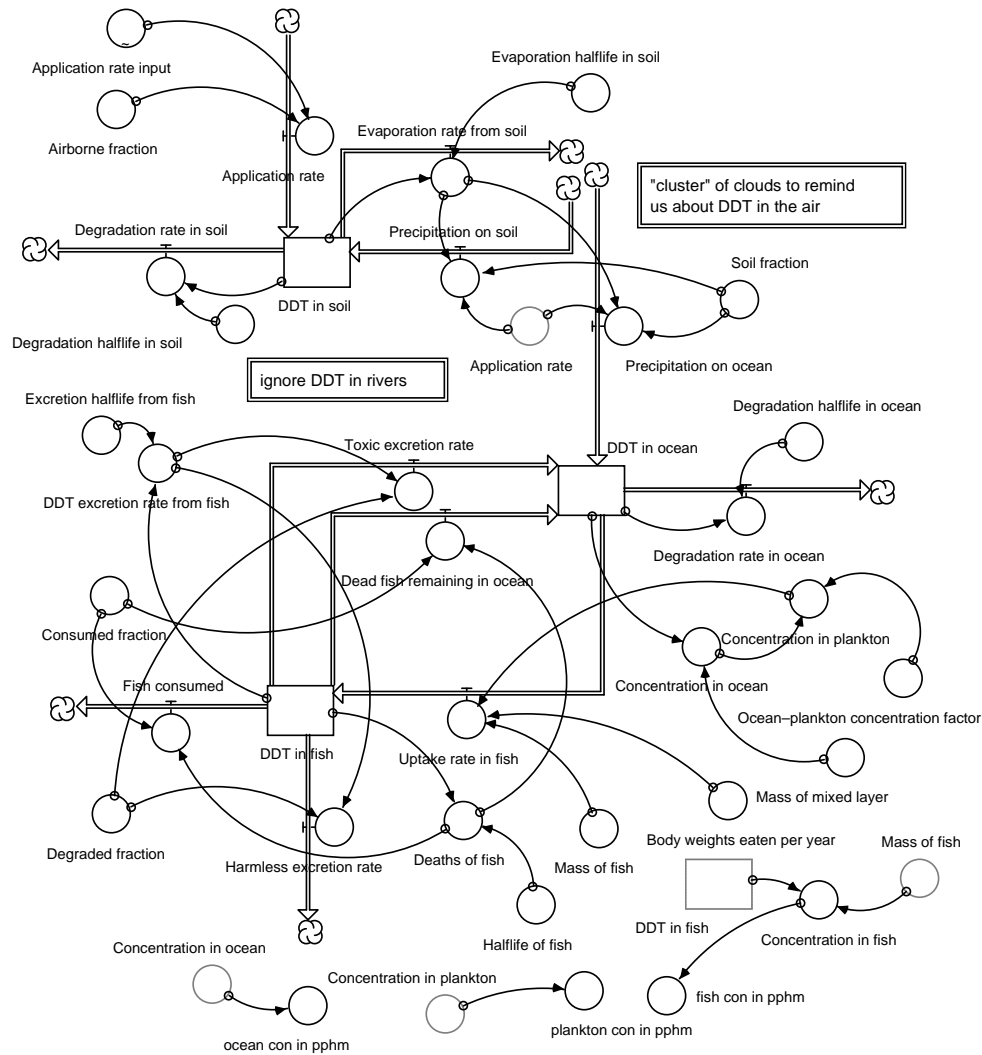


Figure 12.14. Revised model of DDT flows.

This is accomplished by the information connections that link the *evaporation rate from soil* to the *precipitation on soil* and the *precipitation on ocean*. The relevant equations are as follows:

$\text{Evaporation_rate_from_soil} = \text{DDT_in_soil} / (1.5 * \text{Evaporation_halflife_in_soil})$
<input type="checkbox"/> $\text{Precipitation_on_ocean} = (\text{Evaporation_rate_from_soil} + \text{Application_rate}) * (1 - \text{Soil_fraction})$
<input type="checkbox"/> $\text{Precipitation_on_soil} = (\text{Application_rate} + \text{Evaporation_rate_from_soil}) * \text{Soil_fraction}$

The first equation is the same as the previous model. But the next two equations must represent the flow of DDT via precipitation into the ocean or back to the soil. They do this by working directly with the two flows that lead to airborne DDT and the *soil fraction*. Figure 12.15 confirms that the revised model gives the same pattern of results as the original model. The relative timing of the peaks and the long time interval required for DDT in fish to return to the 1962 level are the same as shown previously. The new model delivers the same important insights as the original model.

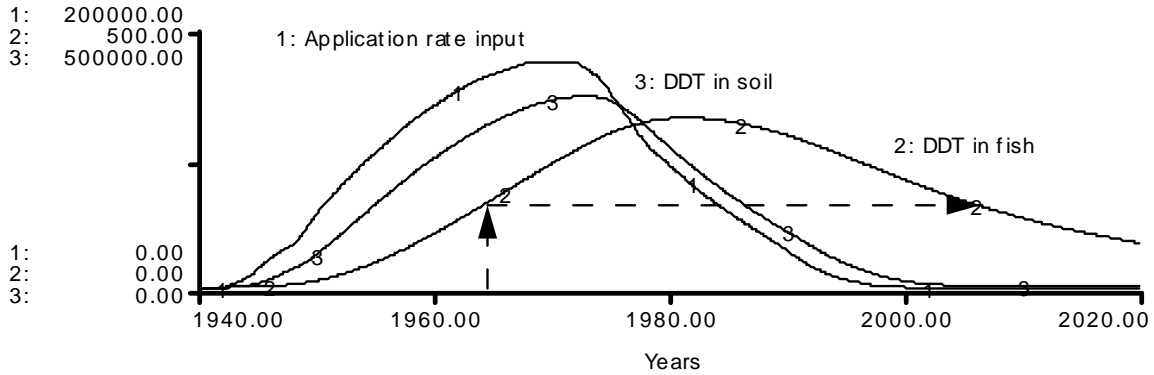


Figure 12.15. Base Case Simulation of the Revised DDT Model.

The revised model does more than match the general trends in the original model; it matches the numerical values quite closely as well. Figure 12.16 provides a summary taken from the year 1980, the year with the maximum value of DDT in fish. It shows that the revised model matches the original model exactly in terms of the DDT stored in the fish, and it comes quite close to the values in the soil and the ocean.

	Original (metric tons)	Revised (metric tons)
Soil	268,362	269,301
Air	10,293	n.a.
Rivers	54	n.a.
Ocean	2,014,124	2,016,528
Fish	329	329

Figure 12.16. Numerical Results from the Year 1980.

The revised model results were generated with a DT of 0.125 years. At 8 steps per year, the 80 year simulation requires 640 steps. We are now operating within the suggested guidelines for numerical simulation.

Summary and Discussion

This chapter demonstrates with an example of DDT how system dynamics may be used to simulate the flow of materials through multiple media like soil, air and water. The demonstration makes use of step tests and equilibrium diagrams to help us appreciate which of the many pathways dominate the system. The demonstration also arrived at two versions of a multi-media model. The two models present us with an interesting question--which of the models is better? The revised model certainly executes more quickly on the computer, and it does so without loss of accuracy. If we intend to conduct extensive sensitivity testing, we could certainly reduce the time in front of the computer with the revised model. But many students find the original model more appealing because it is easier to “see the flows” of DDT through the environment. They understand the logic behind the revised model, and they understand that the two models yield the same numerical results. Nevertheless, they are drawn to the original model, and they are willing to “pay the price” sitting in front of the computer waiting for a slower simulation to appear on the monitor. Their choice is entirely reasonable since modeling is more than making calculations--it’s also a process to improve understanding and communication.

The DDT example involves material flow through multiple media where the individual flows may be described as a diffuse flow with a characteristic half-life. Not all of nature’s flows follow this pattern. Some flows are much more tightly controlled, as when animals migrate to ocean. You’ll see how these flows are simulated in the next two chapters. Appendix I rounds out the treatment of material flows with simulations in the spatial dimensions.

Exercises

A good way to practice is to build either the model in Figure 12.10 or in Figure 12.14. Then verify that they give the results shown here. Exercises 1-4 are relatively easy. Exercises 5-8 will take more time. .

1. Update the Base Case Simulation

The base case results in Figures 12.13 and 12.15 assume that use of DDT would be gradually eliminated by the year 1998. It appears that world-wide DDT use is higher than Randers' base case assumptions. Update the "base case" run with current information on the use of DDT around the world. Document the new base case with a graph corresponding to Figure 12.15.

2. Equilibrium Diagram for the Ocean and Fish

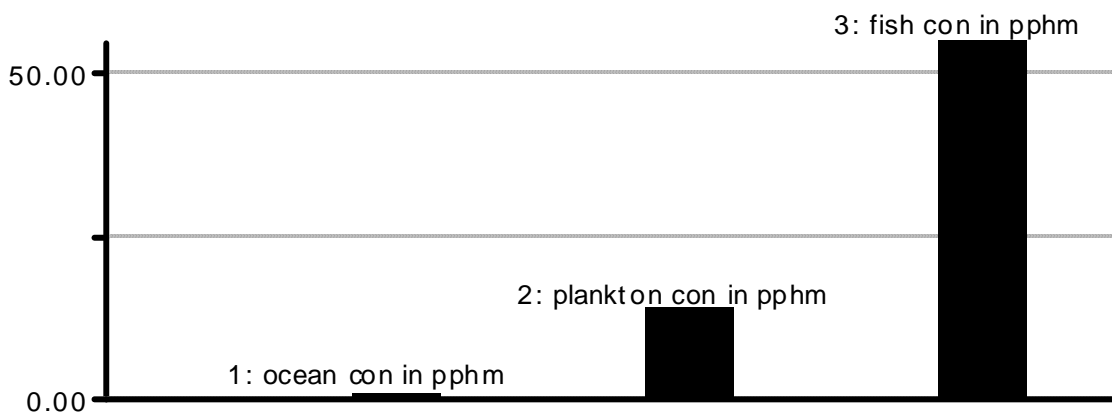
Subject the revised model to the "step test" shown in Figure 12.11. Allow the test to run sufficiently long for the *DDT in fish* to reach equilibrium. Draw an equilibrium diagram for the bottom half of the model.

3. Importance of Half-Life Conversion Factor

Randers uses an approximate conversion factor of 1.5 in each of the flow equations involving a half-life. Chapter 10 explains that the conversion factor appearing in flow equations should be set to 1.44. Conduct a test with the revised model to learn if the change in the conversion factor leads to significant changes in Randers' base case simulation.

4. Bar Chart for Bioconcentration

Repeat the base case simulation shown in Figure 12.15 with the bar chart open to see the "ups-and-downs" of the relative concentrations. Document your work by pausing the simulation in the year 1980 and printing the bar chart below. The three concentrations are measured in parts per hundred million (pphm) to allow for a visual check on the bioconcentration as DDT moves up the ocean food chain



5. Do We Need a Separate Stock for DDT in Fish?

Randers uses a BCF, a bioconcentration factor, to calculate the DDT concentration in the plankton, but he assigns a separate stock variable to keep track of DDT in the fish. Run the base case in Figure 12.15 to learn if this extra stock variable introduces a delay between the accumulation of DDT in the ocean and in the fish. Could you eliminate the stock variable and use a BCF instead? If so, calculate the value of the BCF and revise the model. Run the new model to learn if you get the same results as shown in Figure 12.15.

6. DDT in Birds

Randers' model follows DDT up the chain, but he stops short of the top carnivores. Expand the model to simulate DDT uptake in birds. Use the expanded model to learn whether the "return to 1962 results" is significantly different than shown in Figure 12.15. Add the concentration in birds to a bar chart (as in the 4th exercise).

7. DDT in Farm Workers

Farm workers are exposed to DDT immediately after its application. Expand the model to simulate DDT uptake in workers who are exposed to DDT use during its application and when it evaporates from the agricultural fields. Run the expanded model to study the time delays that are analogous to the "fifty year return interval" for fish shown in Figure 12.15.

8. Regions A & P

Miller (1997, p.388) describes a "circle of poison" involving the production of DDT in the United States for sale to countries that have not adopted the ban. DDT residues may return to the US by several pathways such as fruits and vegetables, migrating birds, and airborne DDT. Expand the model to simulate DDT use in two regions. Region A continues to allow DDT; region P prohibits its use. Assume that the principal pathway connecting DDT in the two regions is the drift of airborne DDT. Adopt the same half-lives for both regions. Assume that DDT use is 50,000 metric tons/year in both regions until the year 1970. After 1970, DDT use falls to zero in region P but remains constant at 50,000 metric tons/year in region A. Run the "A & P model" with a variety of assumptions on the fraction of airborne DDT from region A that drifts over the coastal waters of region P. Use the model to learn how much longer DDT levels in region P will remain above dangerous levels due to the continued use in region A.