Dynamic Simulation of a Thermal Water Quality Trading Program and Implications for Policy Design

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Abstract

This paper describes the Riparian Shading Simulator, a system dynamics model of a thermal water quality trading program, in which point sources are allowed to offset their effluent by paying landowners to plant shade trees. The model is used to explore consequences of policy designs with varying trading ratios and upstream-only rules. Results from the model can be used to help choose a trading ratio that balances the goals of enhancing ecosystem services and reducing costs. The model also indicates that policy makers should be careful about using upstream-only rules, since they can potentially cause shading to be concentrated in upstream areas and contribute to downstream hotspots.

Key words: thermal water quality trading, environmental policy design, trading ratio

Introduction

Thermal water quality trading is an emerging policy tool for managing water temperature. Temperature trading programs give point source thermal polluters the option to comply with effluent restrictions by paying nearby landowners to plant shade trees. The shade trees cool the water, offsetting the thermal pollution emitted by the point source. Thermal water quality trading can be set up within the current system for regulating water quality, by explicitly allowing trading in an effluent permit.

Only one thermal trading program has been implemented to date, on the Tualatin River in Oregon (Clean Water Services 2004). However, water quality trading has been used to manage pollutants other than temperature, including nutrients and chemicals, throughout the United States (Breetz et al. 2004). These programs can involve trading between any combination of point sources and nonpoint sources of pollution. The design of a water quality trading program is usually specific to the particular program (CTIC 2006), since differences in pollutants, traders, and conditions make each situation unique.

Two of the main benefits of using thermal water quality trading instead of conventional regulation are improved cost effectiveness and increased ecosystem services. Both of these factors can be heavily influenced by the specific design of a trading program. Much of the discussion on the development of these markets has revolved around how to set trading ratios. When a trading ratio is used in a water quality trading market, the value of a credit is weighted based on how it is created. For example, credits generated by nonpoint sources are often valued less than credits generated by point sources because more uncertainty is involved in nonpoint source pollution reduction. Another major policy design issues for thermal water quality trading markets is determining whether there will be geographic limitations on trading. This is likely to involve implementation of rules that require trades to be conducted only upstream from the point source.

Models are especially useful tools at this early stage of policy development, when the details of policy design are being determined (Meadows and Robinson 1985). Simulation can allow users to explore potential market outcomes under many different scenarios and designs, helping policymakers to understand potential dynamics and uncertainties and ways in which a policy might be designed to help buffer against unwanted results.

This paper describes a model that simulates the dynamic behavior of a thermal water quality trading market with variable trading ratios and an optional upstream-only rule. The model is designed to teach the user what the behavior of such a market might look like under different policy design scenarios. The model presents lessons about choosing a trading ratio and how to design upstream-only rules, and also allows the user to explore the dynamics of these markets over time.

Uncertainty and Trading Ratios

Point sources tend to have relatively steady, predictable effluent levels. Reductions in point source thermal load can be considered relatively predictable because they involve mechanical reduction of thermal load from these sources. When a thermal water quality trading program is implemented, reductions in thermal load are transferred from predictable point sources to significantly less predictable nonpoint sources and offsets. This can substantially increase uncertainty about the amount of thermal load reduction that will be achieved.

In a thermal water quality trading market, point sources are allowed to offset their thermal load using shade trees planted along neighboring riverbanks. This reduces solar insolation to the river, therefore reducing the amount of heat being added to the river. Compared to near-certain thermal load reductions that can be gained by mechanically cooling point source effluent, the nonpoint thermal load reductions contributed by shade trees is quite uncertain.

Numerous factors in a thermal water quality trading market can contribute to uncertainty. One category of uncertainty might revolve around physical characteristics of the system. This could include changes in climate patterns and varying tree growth patterns. Disturbances, such as floods and fires, might alter the amount of shade provided by a trade. The behavior of participants in a market is also uncertain. For example, how will landowners behave when trading credits in the market? Will there be a potential for market participants to pull out of a trade after one is made? Will wastewater treatment plants change their trading behavior if they need to increase their capacity? There is also no guarantee that a trading program will persist into the future, so it may be difficult at first for the market participants to trust that the market design will be unchanged as time goes on.

Trading ratios can be used to counteract uncertainty in a water quality trading program. The uncertainties discussed above, as well as many others, make the cooling potential of a trading program much less certain than the cooling provided by conventional technologies. When a trading ratio greater than one is used, a point source must offset more thermal load through trading with nonpoint sources than it would be required to reduce through conventional regulation. For example, the Oregon Department of Environmental Quality (ODEQ 2005) calculates the offset created by shade using the equation

$$\text{Heat load offset by shade} = \text{Area of stream shaded} \times \text{Increase in shade density} \times \text{Solar insolation rate} \qquad \text{(equation 1)}$$

If a 2:1 trading ratio is applied, a point source that meets its requirements through trading would have to double its offset. Assuming that shade density and the solar insolation rate will hold constant, this point source would have to shade twice the area of stream that it would be required to shade with a 1:1 trading ratio. While the trading ratios discussed here are used to deal with uncertainty, they can also be used to account for other differences between load-reduction sources, including differences in location and in forms of the particular pollutant being added to the water (US EPA 2007).

Hotspots and Upstream-Only Trading

A trading policy may also place geographic limitations on trades. Hotspots in environmental markets are often a concern, since a market might introduce the possibility of offsetting thermal load in a different location than the one in which the thermal load is produced. In a thermally polluted river, this might occur when a trade is made between a point source and a downstream landowner. In this case, the effluent created by the point source would warm the river, and the water would stay warm until it reached the shaded area. The warm section in between would be considered a hotspot.

Trades must be conducted on the water body where the point source thermal load occurs. A thermal water quality trading policy might further restrict the location of trades by requiring point sources to trade only with landowners who are upstream from the source. This can reduce the likelihood of hotspots as described above (US EPA 2004). If a point source is required to trade only with upstream landowners, its effluent will mix with water that has already been cooled by shading. This would hypothetically reduce the potential for portions of the river to be overheated because of the trading policy.

Previous Simulations and Existing Information

Little information on thermal water quality trading markets currently exists. The Oregon Department of Environmental Quality has put together a policy and sample protocol for temperature trading (ODEQ 2005), as well as a case study report on the Tualatin trade (ODEQ 2007). The U.S. Environmental Protection Agency (US EPA 2004) describes when a thermal water quality trading market should be used.

Two other models have been created to simulate thermal water quality trading markets. Rounds (2007) created a spreadsheet model to simulate the spatial variability in water temperature on the Willamette River under various point source-to-point source trading scenarios. Rounds' model also allows different riparian restoration and dam operation scenarios to be included in the analysis. This model is intended for predicting water temperatures in the Willamette Basin.

Sandia National Laboratories is currently constructing a model to simulate water temperature in the Willamette River (Tidwell and Lowry 2008). This model uses a system dynamics platform similar to the one used in the simulation described here. It simulates water temperatures under different shading scenarios, but does not simulate tree growth or trading behavior. Like Rounds' model, the Sandia model is likely to be used to predict water temperatures under different trading scenarios.

Arquitt (2007), uses system dynamics modeling, the same modeling paradigm used here, to simulate a water quality trading market for nutrients (Arquitt 2007). Arquitt's model focuses on the price and pollution reduction dynamics of the market under different policy designs.

Numerous models have been designed to analyze trading ratios in water quality trading markets. Most of these models are economic optimization models used to find equations for calculating the trading ratio through which a specified environmental goal can be met at the least cost (Malik et al. 1993, Horan and Shortle 2005, Horan 2001, Shortle 1987, Farrow et al. 2005, Zhang and Wang 2002). Woodward et al. (2001) presented a similar model, but use their model to find the trading ratio that would maximize the environmental benefits created by the market. Others have presented alternative models of trading ratios for water quality trading. For example, Hung and Shaw (2005) suggest a system of location-specific trading ratios, while Ning and Chang (2007) suggest time-specific trading ratios.

The simulation described in this chapter is substantially different from all of those described above. Unlike the Rounds and Sandia models, the Riparian Shading Simulator is not meant to be predictive. Instead, it is meant to help users understand potential patterns of dynamics involved in the system. It simulates not only water temperature, but also trading behaviors and tree growth. The Riparian Shading Simulator is also very different from the economic optimization models described above due to its dynamic nature, and because it is not intended for optimization.

The Riparian Shading Simulator

The Riparian Shading Simulator was created using Vensim DS software (Ventana Systems, Inc. 2008). The model has four main sectors: hydrology, heat flows, shading, and trading. The model is quite simple when compared to other models that simulate thermal water quality trading markets (Rounds 2007, Tidwell and Lowry 2008), both because the river being simulated is hypothetical, and because the model is intended for exploring dynamics rather than predicting water temperature.

The hydrology sector of the model (figure 2) simulates water flowing through the river. The river is purely hypothetical, and includes an upper reach and a lower reach with a reservoir in between. Hydrology is important to the temperature of the water because the flow rates control the effects of heat flows, and because the surface area of the river determines the effectiveness of shade trees in cooling the water. Flows through the upper reach are exogenous, and flows through the lower reach of the river are found by using by rule curves that determine the amount of water being released from the reservoir.

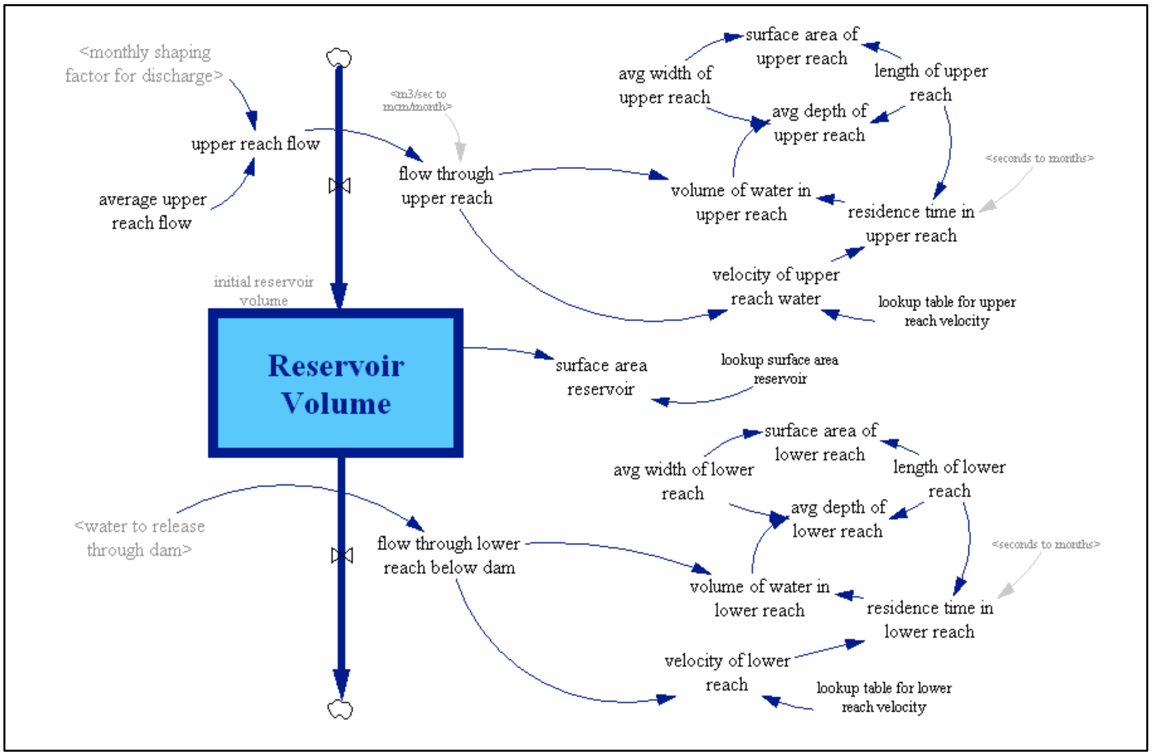


Figure 2: Hydrology sector of the model

The heat flow sector of the model is split up into three sections, for tracking the temperature of the upper reach, reservoir, and lower reach, respectively. The reservoir heat flow section of the model is shown in figure 3, and is very similar to those for the two reaches of the river. The heat flows are based on calculations described by Sinokrot and Stefan (1993) and Evans et al. (1998).

Each section of the river is simulated as a uniformly mixed system, with all heat flows applied to the entire stretch of the river. The seven-day moving average temperature for each stretch is then calculated using a heuristic multiplier. The temperature simulated for each section of the river is the one that would be measured at the most downstream part of that section of the river.

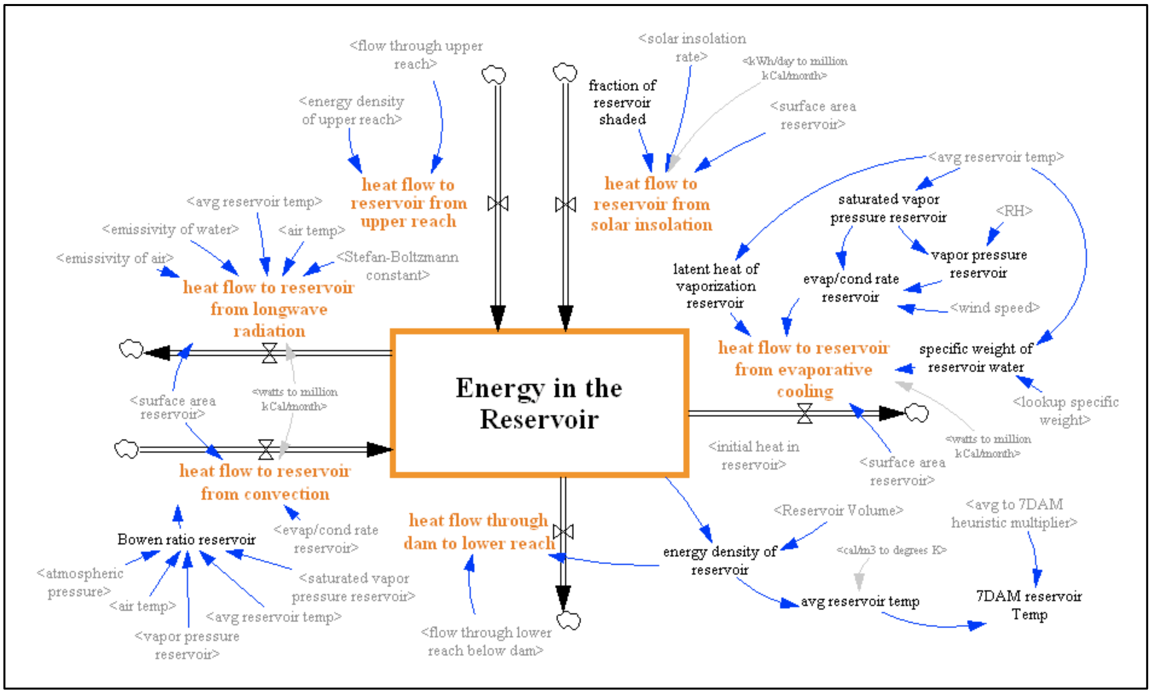


Figure 3: Reservoir heat flows sector of the model

The shading sector of the model simulates the growth of trees that are planted through the trading program. The section of the model that determines shading in the upper reach of the river is shown in figure 4. Trees move between stages of growth at three year intervals. The shading provided by trees in any particular stage is based on a logistic growth curve. In the absence of disturbance, trees will reach their full shading potential 15 years from the time that the trade is initiated. The shade provided by the trading program is added to the initial shading from geology and vegetation to determine the total fraction of the water shaded. The amount of shading affects the temperature of the water by blocking solar insolation, which is simulated in the heat flow sector of the model.

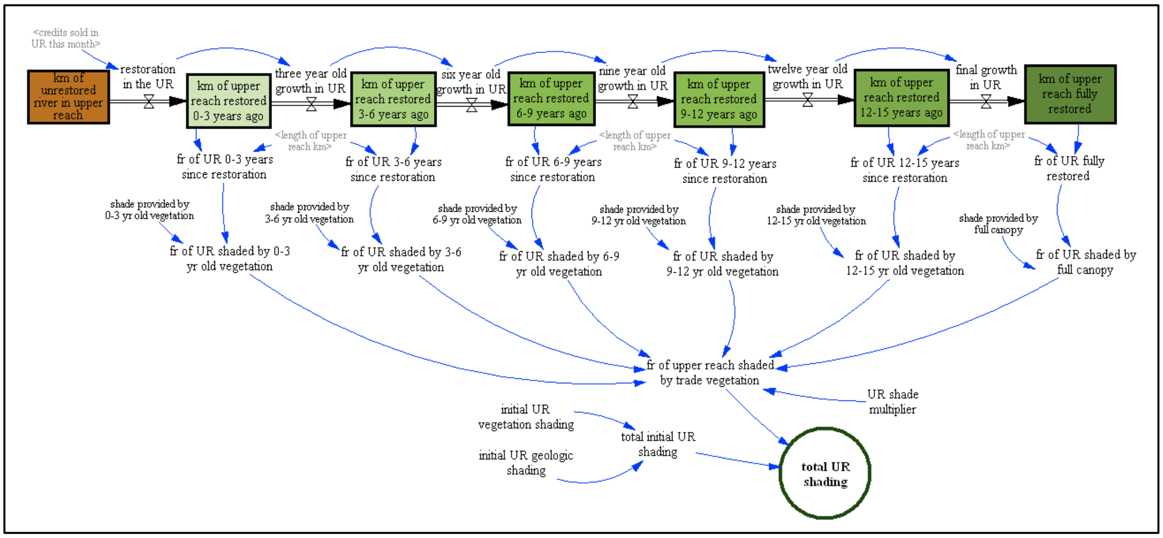


Figure 4: Upper reach shading sector of the model

The final sector of the model simulates the trading of thermal water quality credits. To simulate the price of a credit (figure 5), the model first determines what the interval of possible prices will be. It is important to note that the cost for landowners to create a credit is much lower than the benefit a wastewater treatment plant receives by buying a credit. Therefore, there is a large interval of potential credit prices that will be beneficial to both the buyer and the seller of the credit.

Once the model finds this potential price interval, it chooses a credit price within that interval by determining whether the landowners or wastewater treatment plants have more bargaining power, and to what degree. If the landowners hold all of the bargaining power, then the credit price will be in the highest part of the potential credit price interval, and if the wastewater treatment plants hold all of the bargaining power then the credit price will be at the lowest part of the interval.

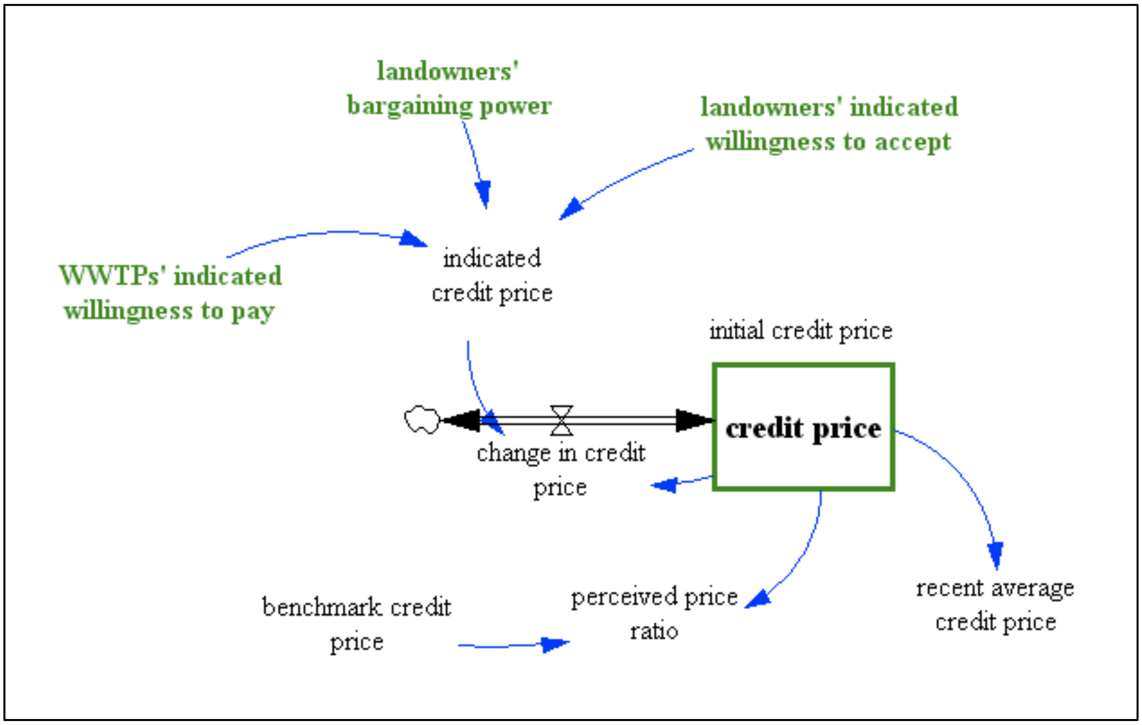


Figure 5: Credit price sector of the model

Each credit sold by a landowner will offset the same amount of thermal load. The amount of shading required to offset a point source's effluent is based on the Oregon Department of Environmental Quality's (ODEQ 2005) equation for heat load offset by shade, shown above in equation 1. Although equation 1 seems to be a quite simple way of calculating offsets, it is currently the policy of the only state with a working thermal water quality trading program. It is also important to note that in and of itself, equation 1 is not a dynamic method of calculating offsets, but when applied in the Riparian Shading Simulator model, the calculation becomes dynamic. For simplicity, the model assumes that the wastewater treatment plant is required to offset the entire thermal load that it contributes to the river. A trading ratio is also applied.

Once the price is determined for a particular month, the supply and demand establish the actual amount of trading that will occur (figure 6). The number of credits desired by each wastewater treatment plant is simulated based on a price elasticity effect. The demand is perfectly elastic. If credits are available to cover the demand then the credits are transferred from the landowners to the wastewater treatment plants. The landowners then plant the shade trees determined by credit sales, and tree growth begins.

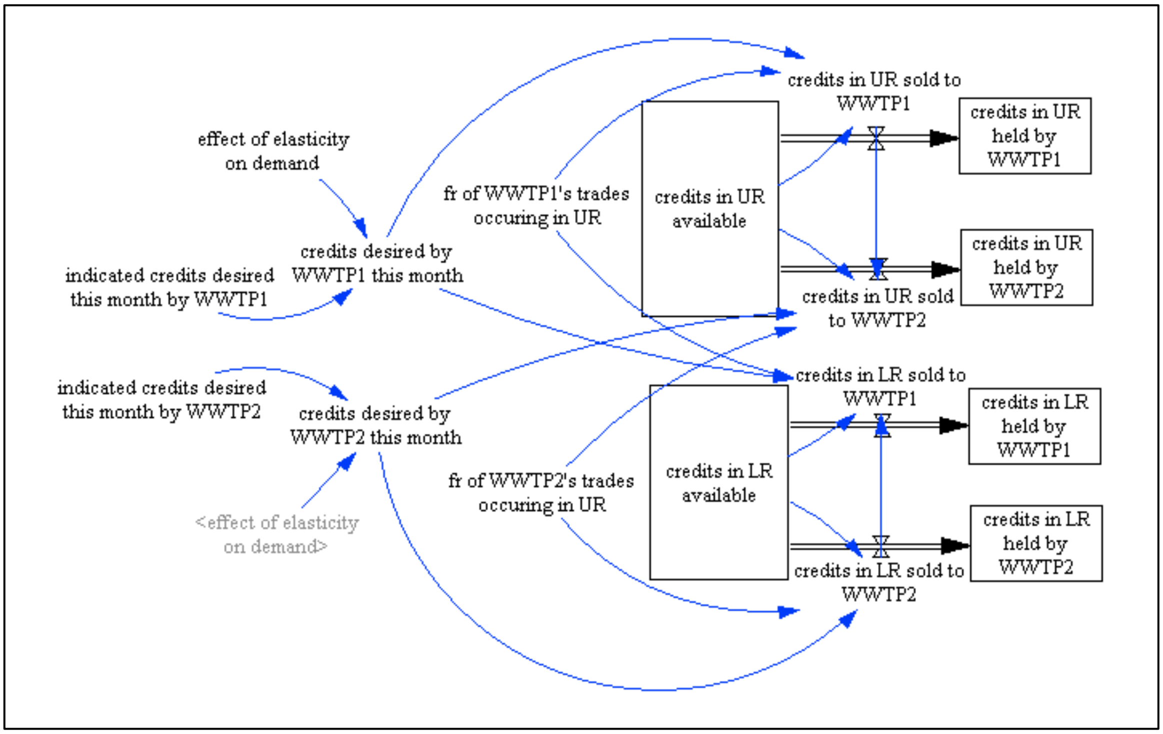


Figure 6: Supply, demand, and credit transfer sector of the model

Simulation Results

Results of the base case simulation of the Riparian Shading Simulator are shown below in figures 7 and 8. In this simulation, the wastewater treatment plants are given ten years to make all the trades needed to comply with the policy. Although the trades are all made within the first 10 years, the shade trees take 15 years to grow. For this reason, the full shading potential of trees planted through the trading program is not reached until the 25th year. The trading ratio is set at 1:1. Since no penalty is applied to shade offsets as compared to mechanical refrigeration, the temperature of the river comes exactly into compliance with the temperature standard when full shading potential is reached. It can be seen through this simulation that without thermal load from the wastewater treatment plants, the river would be exactly in compliance with the temperature standard.

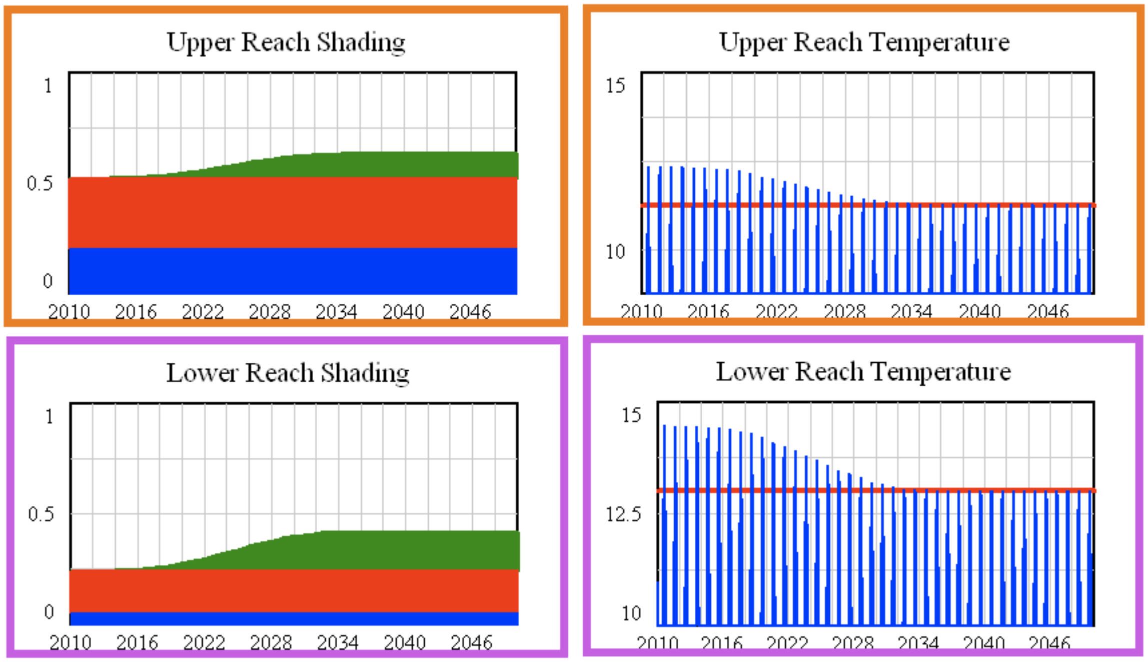


Figure 7: Shading and temperature results from the base case

Figure 8 shows the potential credit price interval, bound by the landowners' willingness to accept on the bottom and wastewater treatment plants' willingness to pay on the top, along with the actual credit price for the portion of the simulation that occurs before the deadline. No trading will occur after the deadline, since any thermal load that has not been offset by that point will be reduced through mechanical refrigeration on the point sources' effluent.

The wastewater treatment plants' willingness to pay for a credit (shown in blue in figure 8) starts at $200,000, and after 12 months begins to increase. This is because as more trades are made, the wastewater treatment plants begin to believe that trading is less risky. Their indicated willingness to pay thus goes up as more trades are completed. The lack of growth of this variable at the beginning of the simulation is due to a lag between trades being initiated and perceived risk decreasing.

The landowners' willingness to accept (the red line in figure 8) begins around $50,000, grows slowly for 12 months, and then begins to decrease. The growth at the beginning of the simulation occurs because the cheapest trades available are sold first, so remaining trades get more expensive as more trades are completed. Like the wastewater treatment plants, the riskiness of trading perceived by landowners decreases as more trades are made, so that the price begins to drop after the 12-month lag between trading and reduction in perceived risk.

Near the beginning of the simulation, the credit price, shown in green in figure 8, is near $100,000. Bargaining power at the point (shown in gray in figure 8) is in favor of the wastewater treatment plants, so the credit price is nearer to the low end of the potential credit price interval. There are a few reasons why the wastewater treatment plants have more bargaining power than the landowners early in the simulation. First, there is quite a lot of time until the deadline, so little pressure is being felt by the wastewater treatment plants to make their trades right away. Second, since few trades have so far been made, there are quite a few potential credits left to buy. The final factor that enters into the determination of bargaining power is current demand for credits. Since the credit price is low in the beginning of the simulation, demand for credits is relatively high (figure 9). However, this effect on bargaining power is not large enough in the beginning of the simulation to outweigh the time pressure and remaining credits factors, so bargaining power leans toward the wastewater treatment plants.

As the simulation moves forward, the time and remaining credits pressures begin to sway bargaining power in favor of the landowners. This causes the credit price to push upward toward the high end of the potential credit price interval. By the end of the simulation, the price is over $300,000 per credit. The total cost of compliance with the policy for the wastewater treatment plants in the base case simulation is $22 million. Had the plants decided not to trade, and instead to purchase refrigeration units, compliance would have cost $100 million.

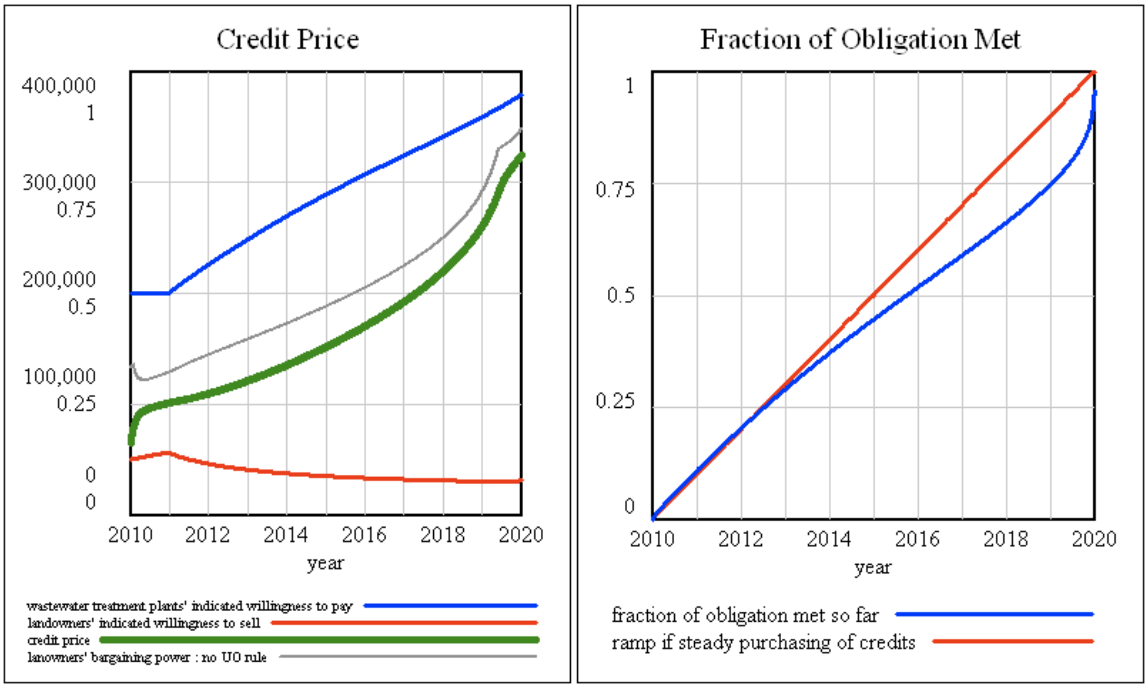
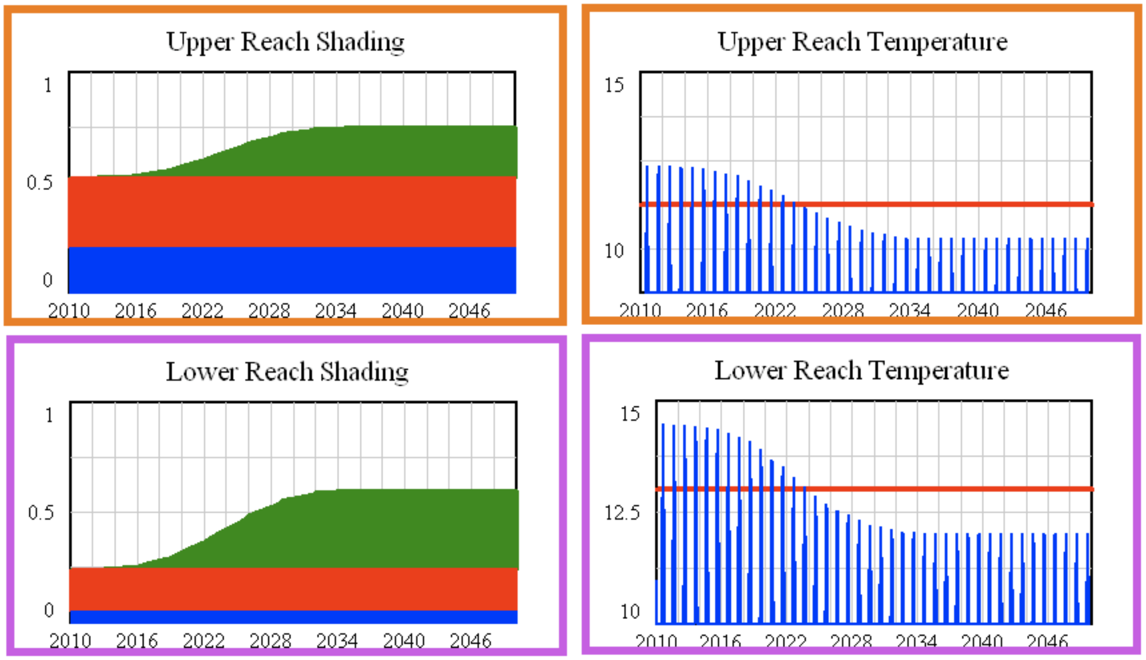


Figure 8: Credit price formation and fraction of obligation met in the base case

The next simulation was run with the same settings as the base case, except that the trading ratio was set at 2:1. Results of the 2:1 trading ratio scenario are shown below in figures 9 and 10. The 2:1 trading ratio indicates that any reduced thermal loading achieved by shading only offsets half of the same thermal loading produced by a wastewater treatment plant. Therefore, if a wastewater treatment plant uses shading to comply with regulation, it will have to complete trades that cool the river twice as much as it would have to if a 1:1 trading ratio were used, as in the base case. This means that in this model, a 2:1 trading ratio results in the river being cooled well below the temperature standard (figure 9).


Upper Reach Shading

Upper Reach Temperature

Lower Reach Shading

Lower Reach Temperature

Figure 9: Shading and temperature results from the 2:1 trading ratio scenario

In this simulation, the wastewater treatment plants' willingness to pay (figure 10), which forms the top boundary of the potential credit price interval, starts at $100,000. This is half of what the willingness to pay was in the base case scenario. This is because of the trading ratio. When the trading ratio doubles, twice as many credits are required to offset a given amount of shading. This means that any particular credit will save a wastewater treatment plant only half of what it did with a 1:1 trading ratio. Thus, the initial willingness to pay for one credit is cut in half when the trading ratio doubles.

Like in the base case simulation, bargaining power in the 2:1 trading ratio simulation begins in favor of the wastewater treatment plants, and moves in favor of the landowners as time progresses. Since the wastewater treatment plants' willingness to pay in this scenario starts out lower than in the base case, the price stays quite low for the first part of the simulation. The price does not reach $100,000 until the third year of the simulation. The low price creates high demand for the first few years. As time goes on and the price increases, demand decreases. The total cost to wastewater treatment plants of complying with the policy in this 2:1 trading ratio case is $31 million. This is less than one and a half times the total cost in the base case scenario, and achieves twice the temperature reduction (figure 9).

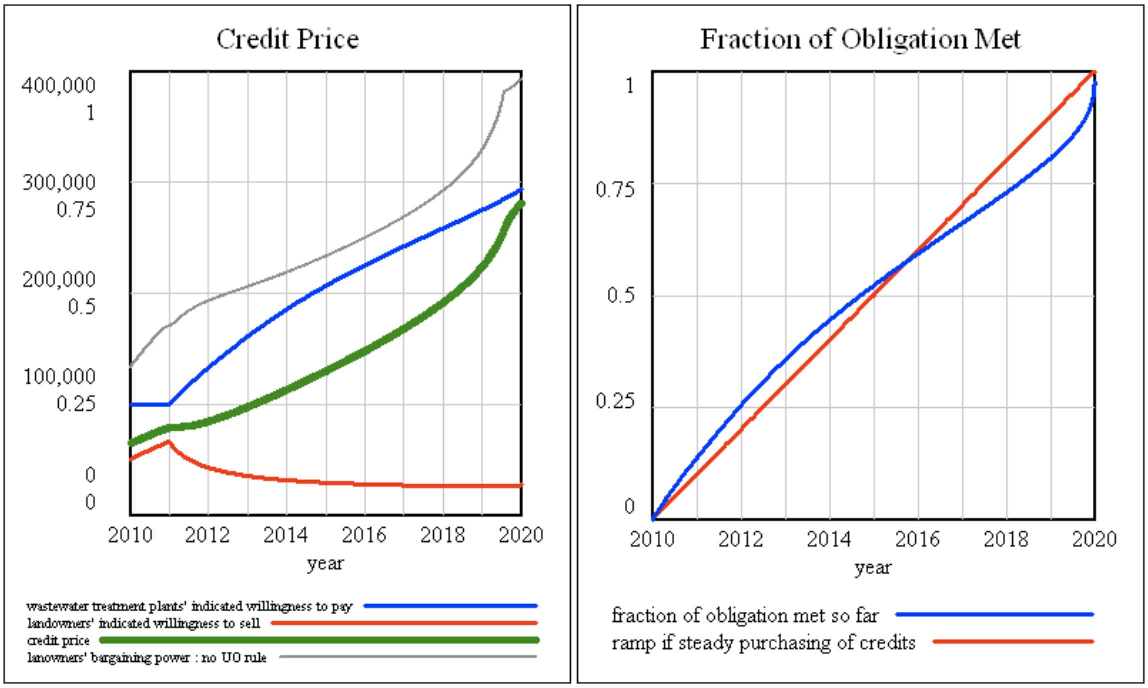


Figure 10: Credit price formation and fraction of obligation met in the 2:1 trading ratio scenario

The third scenario analyzed with the Riparian Shading Simulator includes a 1:1 trading ratio, as in the base case, but adds an upstream-only rule. The wastewater treatment plant in the upper reach of the river is thus required to make trades only with landowners in the upper reach. The wastewater treatment plant in the lower reach is allowed to trade with any landowner. Trading behavior in the upstream-only cases is similar to that in the cases with no upstream-only rule.

The shading and temperature results from the upstream-only 1:1 case are shown below in figure 11. Overall, this scenario sees the same reduction in heat flows due to shading as is seen in the base case. However, the upstream-only rule causes different temperature dynamics to occur (figure 11). The temperature in the upper reach ends up lower than the target, while the lower reach temperature still exceeds the target by the end of the simulation.

Since the upstream wastewater treatment plant can only trade in the upper reach of the river, all of its offsets are made in the upper reach. The downstream wastewater treatment plant, however, is allowed to trade anywhere along the river, and thus makes some trades in the upper reach and some in the lower reach. Because of this, a larger portion of trading occurrs in the upper reach than in the base case. This causes more cooling to occur in the upper reach by the end of the simulation. Since so much of the shading is created in the upper reach, less is created in the lower reach in this simulation than in the base case.

Some of the extra cooling realized in the upper reach transfers to the lower reach, but not enough to cool the lower reach as much as in the base case. Cooling realized by shading will be the highest in the area where shading occurs. Benefits of upstream shading do include cooler water downstream from the shaded area, but the cooling effect is reduced as the water moves downstream (Rounds 2007).

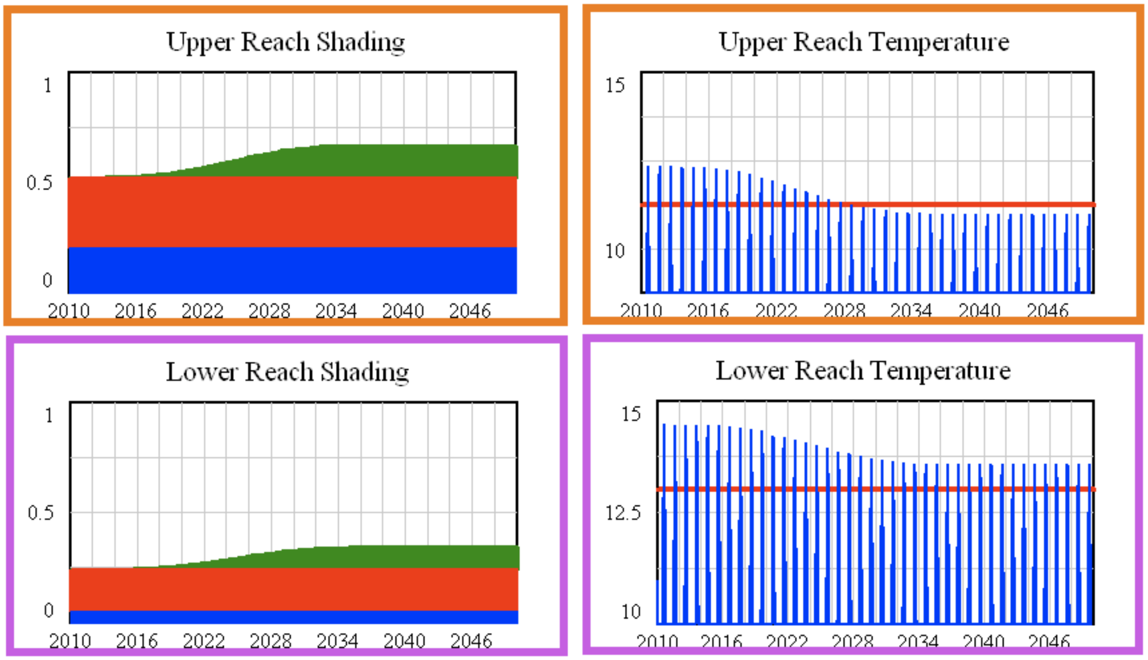


Figure 11: Shading and temperature results from the upstream-only 1:1 scenario

The fourth scenario run with the Riparian Shading Simulator is an upstream-only case with a 2:1 trading ratio (figure 12). Like the upstream-only 1:1 case, this scenario sees more shading occurring in the upper reach of the river than in the lower reach. Because the trading ratio is higher in this case, both sections of the river have a temperature below the target by the end of the simulation. However, the upper reach temperature ends up much farther below the target than the lower reach temperature.

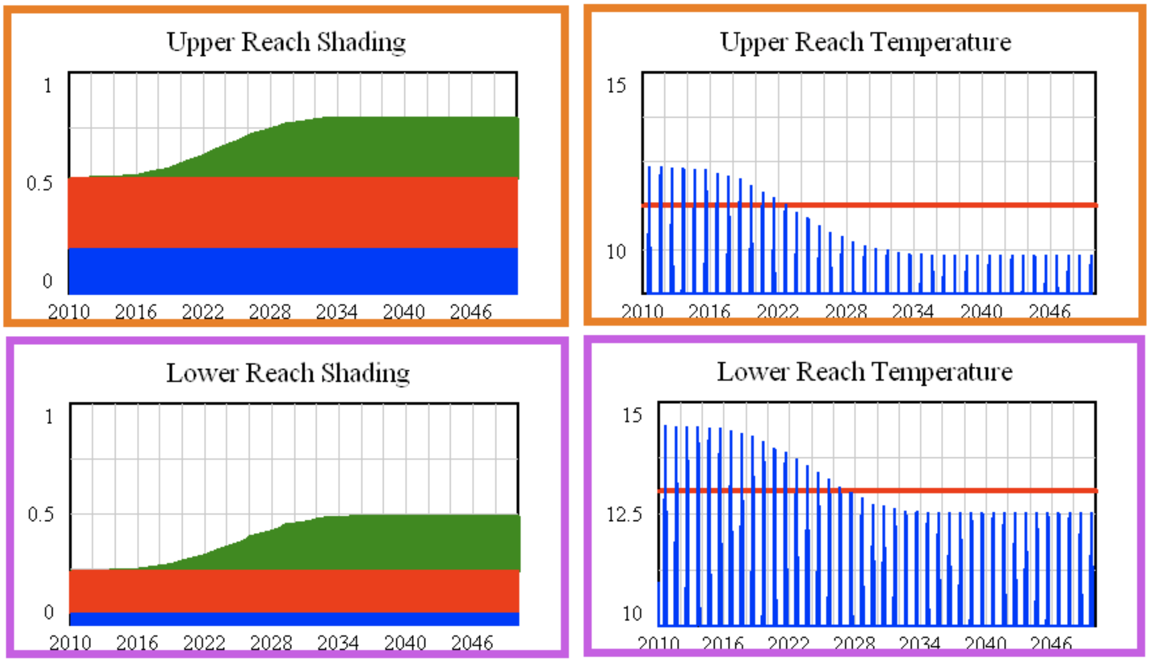


Figure 12: Shading and temperature results for the upstream-only 2:1 scenario

Lessons for Policy Makers About Trading Ratios

The choice of a trading ratio will have a major impact on the overall cost of a thermal water quality trading program, as well as on the environmental benefits achieved by the program. We can discuss how the trading ratio effects these costs and benefits by analyzing the simulations described above, along with a few more trading ratio scenarios.

Figure 13 shows how the total compliance cost changes as the trading ratio moves from 1 to 2.5. Since a higher trading ratio requires wastewater treatment plants to make more trades, the total cost of compliance (the blue line in figure 13) with the trading policy increases as the trading ratio increases. Figure 13 also shows the cost of complying with temperature regulations if trading is not used. The refrigeration units that would be required in the absence of trading cost $50 million for each wastewater treatment plant, or $100 million total. Even with a trading ratio of 2.5, the total cost to wastewater treatment plants is substantially lower when trading is used than it would be without trading.

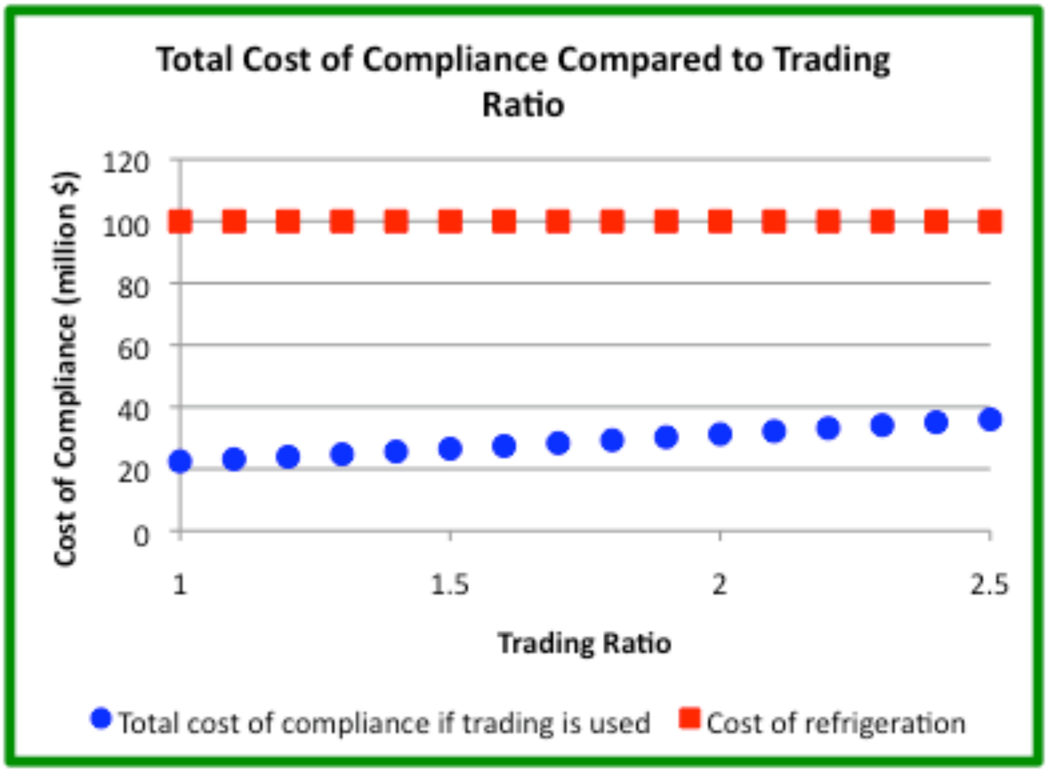


Figure 13: Total compliance cost for specified trading ratios, using trading versus using refrigeration

It is also important to remember that as the trading ratio increases, more benefits are realized from the policy. The benefits are likely to include various additional ecosystem services. To simplify our discussion, we consider the decrease in water temperature as a proxy for the total benefits realized through the policy. Figure 14 shows the change in water temperature with various trading ratios in the upper and lower reaches of the river during the warmest part of the summer, when the temperature of the river is most likely to be out of compliance with the target. The blue line at the top of each chart is the water temperature at the beginning of the simulation, and the green line shows the water temperature that is achieved after trading is completed and the trees involved have been given time to grow. The red line in between represents the target water temperature indicated by regulators. In both river reaches and for all trading ratios higher than 1:1, the trading policy reduces water temperature below the indicated target.

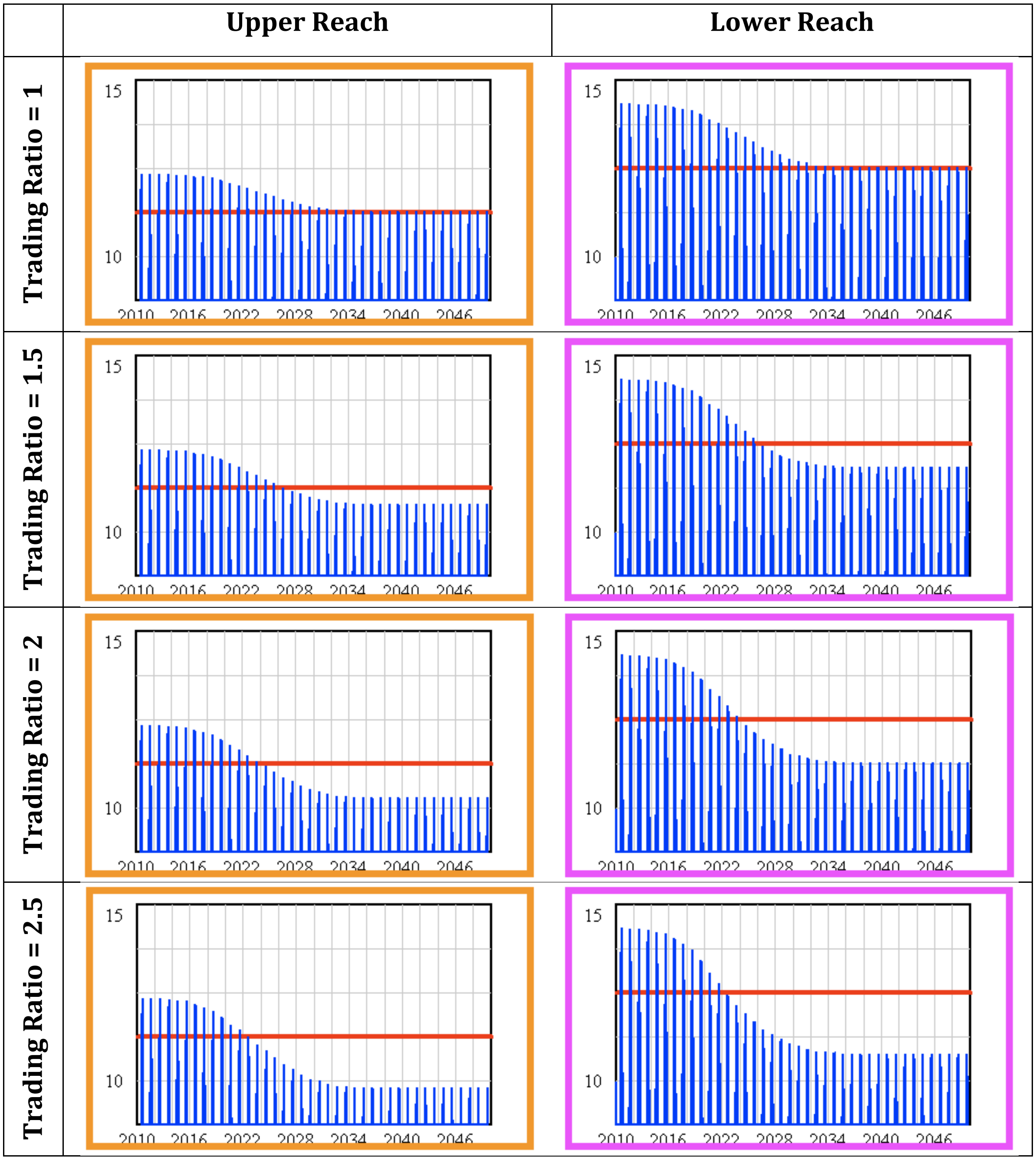


Figure 14: Change in water temperature from shading in the upper and lower reaches for different trading ratios

From the information shown in figure 14, we can determine the decrease in water temperature realized by the trading policy for each reach of the river and at each trading ratio. The decrease in temperature due to trading for the upper and lower reach by trading ratio is shown in figure 15. As the trading ratio increases, the amount of cooling produced by the trading program increases.

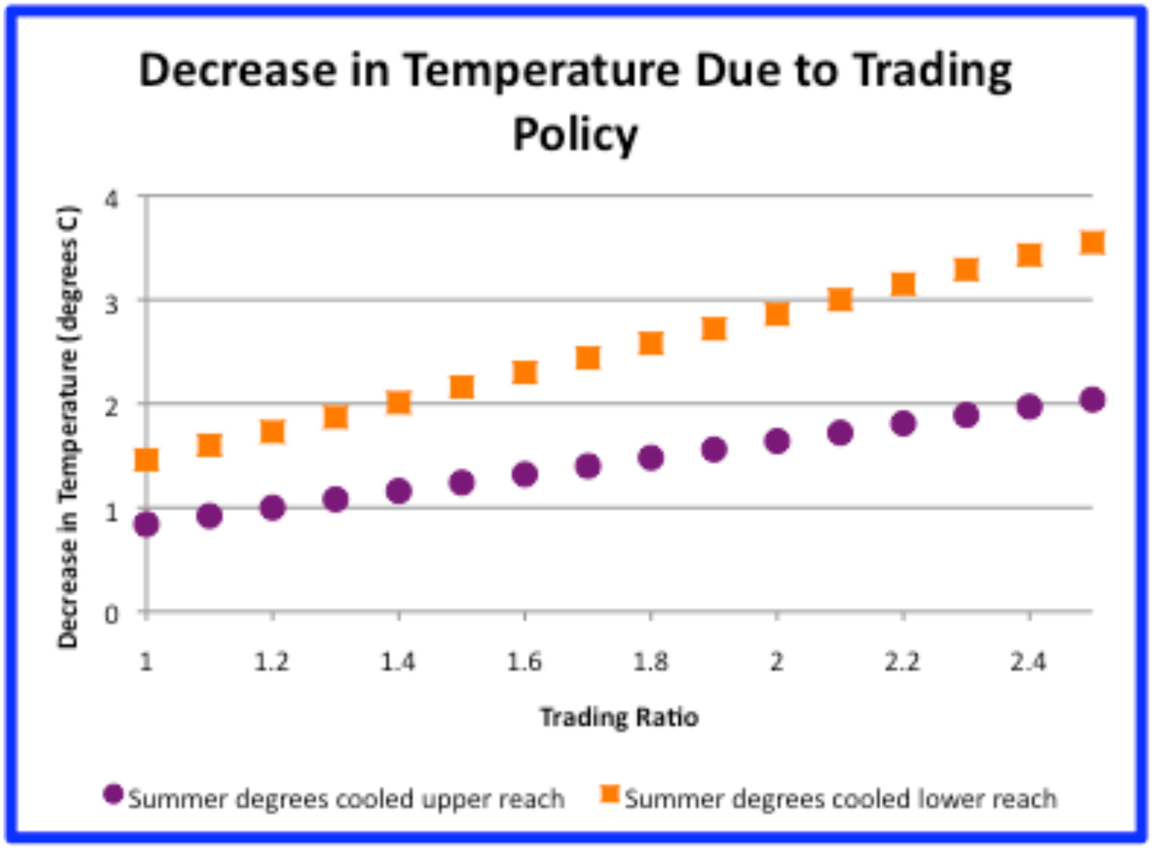


Figure 15: Decrease in temperature in the upper and lower reach due to trading at various trading ratios

From the information above, we can create a measure that will serve as an overall indicator of the benefits produced by a trading program. This measurement will be calculated as the average of the degrees cooled by the program in the upper reach and the degrees cooled by the program in the lower reach. It is important to note that this number represents far more ecosystem services than just the cooling it describes. It should be considered a proxy for the cooling of the water as well as all of the additional ecosystem services produced when riparian vegetation is restored.

Figure 16 shows how the costs and benefits of a thermal water quality trading market will change as the trading ratio varies, as well as what those costs and benefits would be if conventional effluent refrigeration were used instead of trading. With the trading ratio set at 1, the total cost of $22 million creates a benefit of 1.15 degrees. By increasing the trading ratio to 1.5, extra benefits indicated by a .55 degree cooling value are created at a cost of $4 million more. In order to determine whether the 1.5 trading ratio is preferential to a trading ratio of 1, a market designer can weigh the cost against the benefits provided when shading reaches a level that will cause a .55 degree cooler river (averaged between reaches). These benefits will include cooling, but also other ecosystem services provided when the extra shade trees are planted.

Similarly, a trading ratio of 2 provides additional benefits of .55 degrees of cooling at a cost of $4 million, and a trading ratio of 2.5 adds .55 degrees of cooling at a cost of $4 million. In order for a market designer to choose an appropriate trading ratio, they can determine the dollar value of the specified increase in ecological and other benefits, and weigh that monetary benefit against the cost of increasing the trading ratio. As the trading ratio increases, costs to the wastewater treatment plants will increase, but if the ecosystem service benefits of the higher trading ratio outweigh those costs, then the higher trading ratio should be applied in order to increase the overall benefit to society. It is also important to remember that a substantial time lag exists in the system, so that the full costs and benefits will not be realized until all trading has occurred and trees have grown to their full shading potentials.

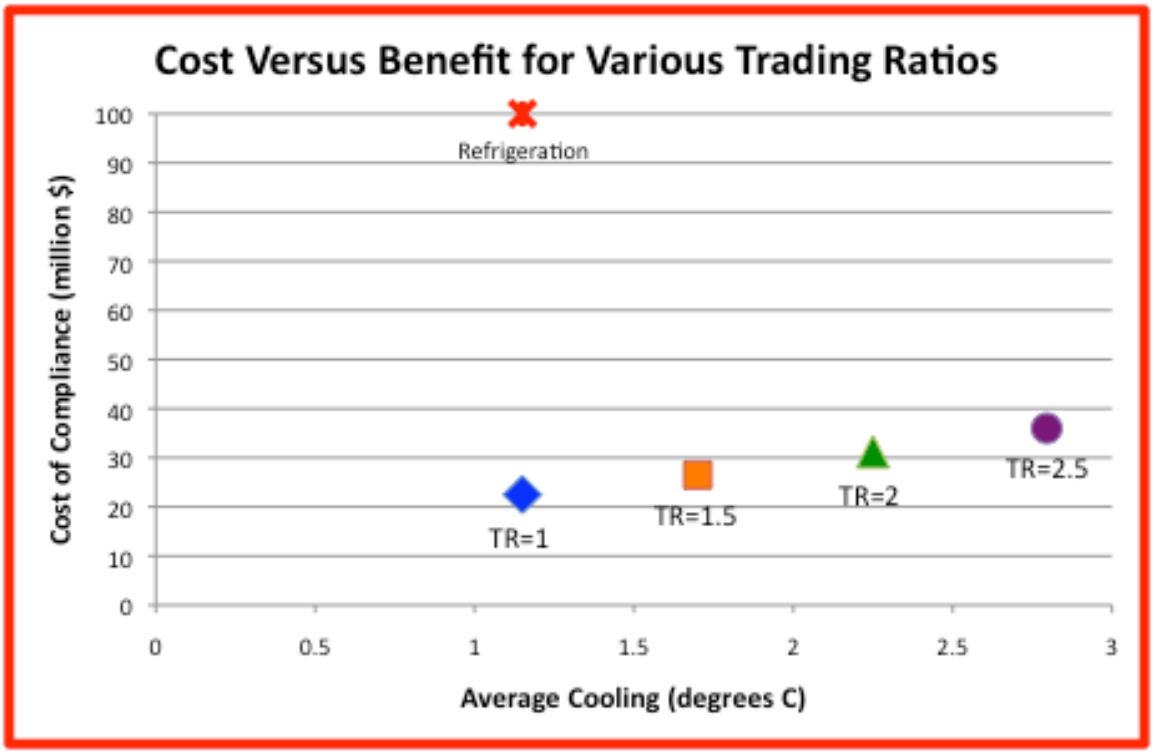


Figure 16: Cost and benefit of a thermal water quality trading policy with various trading ratios

It is also important to notice that this model does not simulate uncertainty in determining the costs and benefits provided by each trading ratio. Uncertainty will create intervals of potential benefits or costs around any point on the chart shown in figure 16.

For example, consider the case where a disturbance occurs after trees are planted. For the purpose of this discussion, assume that a fire destroys half of the trade vegetation in the area, which will afterward begin to grow back at the same rate as before. If the trading ratio were set at 2:1, and this fire eliminated half of the trade vegetation, the benefits of the trading program would temporarily be cut to the level of benefits seen in the 1:1 trading ratio scenario without the fire. Because of the trading ratio, the wastewater treatment plants' thermal load would still be counteracted. The uncertainty that would be added by such a fire would create an interval of cooling benefits, as shown below in figure 17. A disturbance such as this would be temporary, so the benefits realized through the trading program would be reduced from 2.25 to 1.15 after the fire, but would climb back to 2.25 over time.

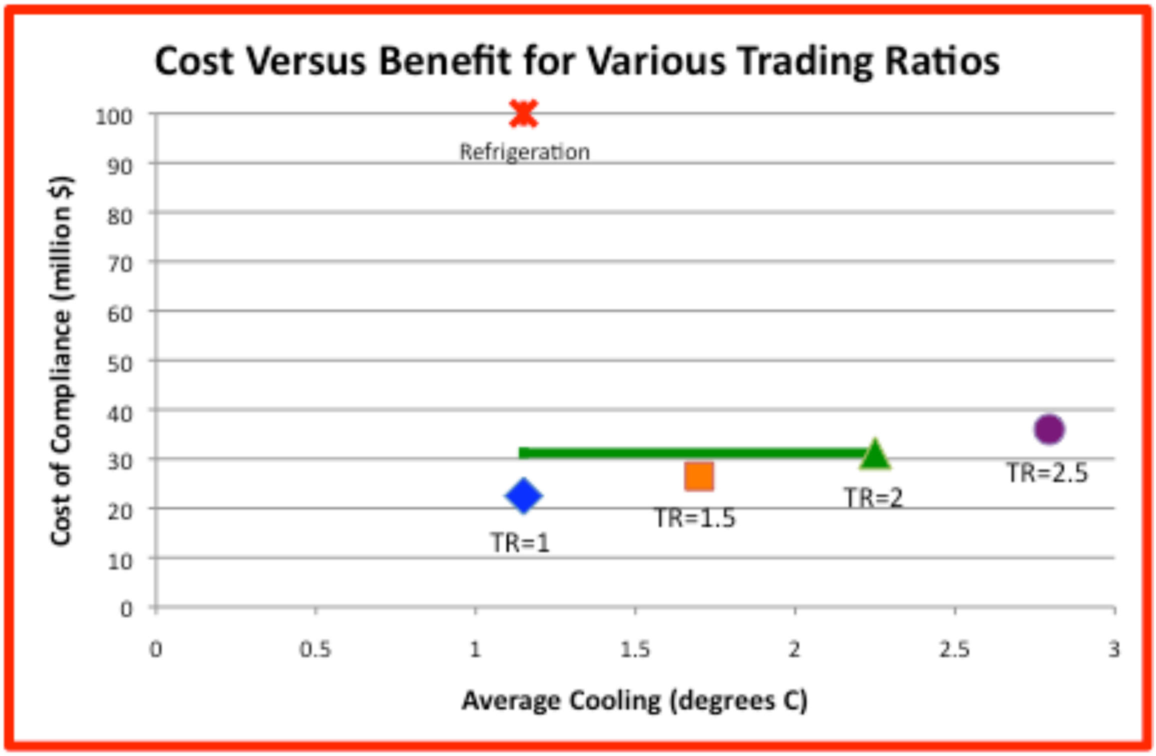


Figure 17: Cost and benefit of a thermal water quality trading policy with various trading ratios, with uncertainty in average cooling due to fire for the 2:1 trading ratio shown

Uncertainties may also alter the cost of choosing a particular trading ratio. For example, if a landowner decides to pull out of a trade, then the wastewater treatment plant might have to pay for mechanical refrigeration of effluent even in the presence of a trading policy. As an example, consider the case where 5% of trades fall through and wastewater treatment plants have to pay an additional $5 million for the refrigeration of that portion of their effluent. The cost uncertainty interval for this scenario occurring with a 2:1 trading ratio is shown below in figure 18.

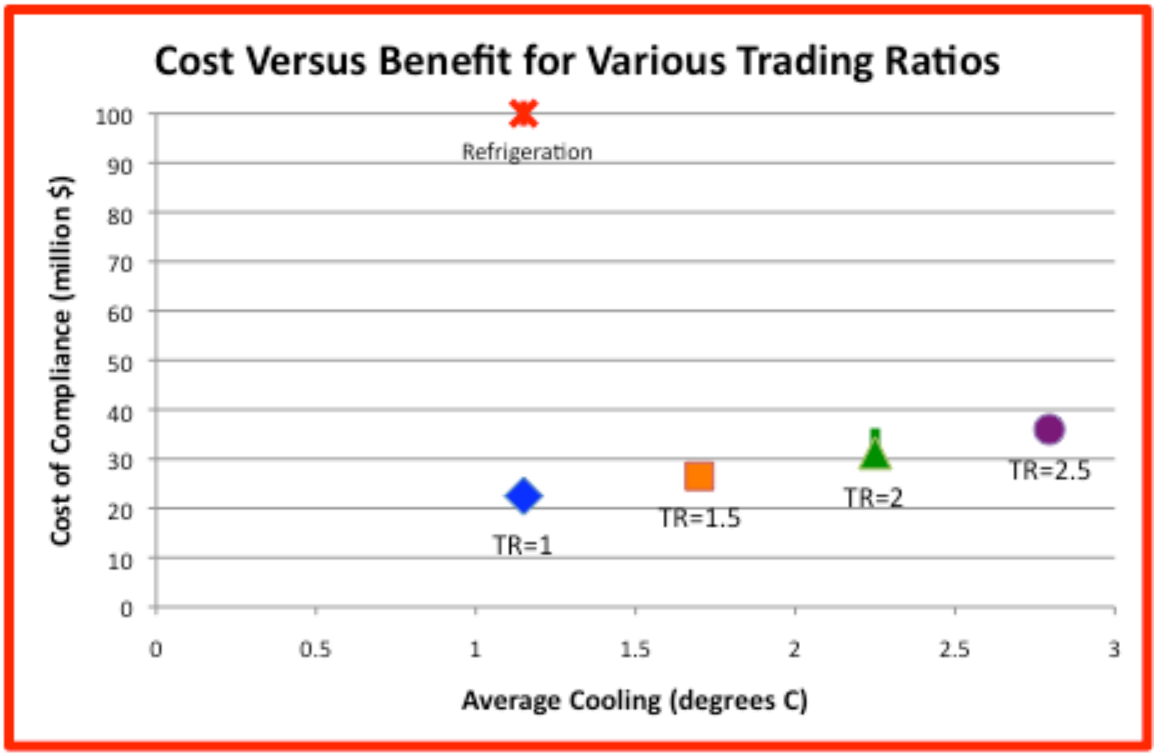


Figure 18: Cost and benefit of a thermal water quality trading policy with various trading ratios, with cost uncertainty due to landowner pullout for the 2:1 trading ratio shown

These uncertainties create intervals of potential benefits and costs rather than the points shown in figure 16. Cost benefit analyses may be used on the singular points, but policy designers should also consider the potential for costs and benefits to vary within some range of uncertainty.

Lessons for Policy Makers About Upstream-Only Rules

The results for simulations in which upstream-only rules were applied show that with these rules in place, more trades occurred in the upper reach of the river than in the lower reach. This type of policy rule is meant to discourage hotspots by ensuring that shading not occur downstream from a point source, which could allow warmer sections of water in between the point source and the shading.

The most important result from the upstream-only simulations discussed here is that when trades were concentrated in the upper reach because of an upstream-only rule, there was less cooling in the lower reach than in the simulations without the rule. By attempting to protect the water in the upper reach from absorbing more of its share of heat, the upstream-only rule actually caused the lower reach of the river to be overheated compared to the simulations without an upstream-only rule.

It is likely that the arrangement of the river in the Riparian Shading Simulator overestimates this effect. First of all, a reservoir exists between the upper and lower reaches of the river being simulated. When water enters the reservoir, it sits in a minimally shaded area for quite some time. This allows sunlight to warm the water while it is in the reservoir. The effect of this warming is amplified when the water is cooler, so the well-mixed reservoir in this simulation may be further amplifying the warming affect of the reservoir. In fact, a market might be designed so that separate markets must be maintained between reaches, so that credits generated upstream of a lake are not substitutable for credits generated downstream.

However, it is true that as water moves downstream, the cooling effects given by upstream shading are diminished (Rounds 2007). While the effects seen in this simulation may not necessarily be indicative of the exact amount of lost cooling in a situation where the river is laid out differently, cooling generated upstream will not hold constant as the water moves downstream.

This result indicates that upstream-only rules should be carefully designed so as not to encourage shading to be concentrated in particular areas, including those far upstream in the river system. The market designer must remember that trading upstream of a point source does not necessarily eliminate the issue of hotspots. Policies that encourage point sources to trade both upstream and nearby are likely to be a better option, since they are more likely to reduce the likelihood of shading effects being significantly reduced by the time the cooled water reaches the point of effluent release.

Conclusion

Two policy design options were considered in the simulations described above: the choice of trading ratio, and the choice of whether to institute an upstream-only rule. In all of the scenarios described above, the wastewater treatment plants achieve compliance with thermal load standards through trading with landowners. The cost reductions achieved by using trading make the option more attractive than using direct point source controls. This means that point sources are likely to find trading attractive, so the design of a trading policy can have a major impact on the costs and benefits of thermal load reduction policy.

The model discussed in this paper led to several important lessons about how the design of a thermal water quality trading market can affect its outcomes. Trading ratios affect both the costs and the benefits achieved by the policy, and these two must be balanced against each other when choosing a trading ratio. Upstream-only rules have the potential to backfire. In order to reduce the overall likelihood of hotspots, upstream-only rules should be paired with rules discouraging point sources from trading with landowners very far upstream. The choice of policy design in a thermal water quality trading program can be a strong factor in determining the outcomes of the program, and must be carefully considered by policymakers.

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