Rendering Natural Waters

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Abstract

Creating and rendering realistic water is one of the most daunting tasks in computer graphics. Realistic rendering of water requires that the sunlight and skylight illumination are correct, the water surface is modeled accurately and that the light transport within water body is properly handled. This paper describes a method for wave generation on a water surface using a physically-based approach. The wave generation uses data from the oceanographical observations and it is controlled by intuitive parameters such as wind speed and wind direction. The optical behavior of the water surfaces is complex but is well-described in the ocean science literature. We present a simple and intuitive light transport approach that is easy to use for many different water types such as deep ocean water, muddy coastal water, and fresh water bodies. We demonstrate our model for a number of water and atmospheric conditions.

1. Introduction

Of all the challenges facing those who create computer-generated imagery, one of the most daunting is creating realistic water. To create realistic images of water three components need to be addressed:

1. **Atmospheric conditions:** What direction and magnitude has the wind that generates waves? How much sunlight and skylight reaches the water surface?
2. **Wave generation:** What makes the water look like the ocean?
3. **Light transport:** How does light interact with the water body?

In this paper we address the second and third points only. Our work differs from the previous work described below because we use a methodology customized to the real data available in the oceanographic literature.

Water has many components to its subjective appearance that must be accounted for in any realistic rendering. The water's reflectivity will vary between five and one hundred percent, depending on angle. For angles where the reflectivity is high, the sky will be reflected with little loss of intensity. Where water's orientation reflects the disk of the sun, extremely bright highlights are present. The spatial pattern of such highlights are very familiar. Where the reflectivity of the water surface is low, any light coming from below should be visible to the viewer. This light can be reflected light from the water bottom, or scattered light from the water volume itself. The impurities in the water determine the proportion of scattered by the volume, as well as its color. Thus the familiar brown of muddy water and the deep blue of many tropical waters. To capture the appearance of water, this scattering must be approximated to enough accuracy to recreate these familiar opacities and colors. Minnaert describes many of these effects [10].

Perlin has used noise synthesis approach [15] to simulate the appearance of the ocean surface seen from a distance. More in-depth discussion of water waves in computer graphics was done by Fournier and Reeves [3], Peachey [14], and Tso and Barsky [24] who modeled shallow water waves using different basis shapes. Mastin et al. [9] described a technique long in use by the oceanography community for modeling deep ocean waves.

Knowledge of the radiance distribution within and leaving a water body is a prerequisite for the solution of many problems in underwater visibility, remote sensing, mixed-layer thermodynamics, and realistic image synthesis. Watt describes a backward beam tracing approach to interaction of light with water [26], but his method does not take into account complex optical properties of water bodies. Nishita and Nakamae presented a method that can effectively calculate optical effects [13]. Their method focuses primarily on effects such as caustics and shafts of light in water bodies.

In this paper we describe an approach to modeling water surfaces based on simple atmospheric conditions and solving a light transport in water bodies that is simple and ef-

Figure 1. *Photograph of the ocean (left) and rendering (right) of ocean using technique described in the paper. (see Color Plate*

ficient, and yet accurate enough for many different water types ranging from deep ocean water to muddy coastal waters as well as fresh waters.

2. Wave Generation

The importance of plausible modeling of any water surface is two fold. First, the visual characteristics of water surfaces especially oceans are very distinct. Second, it has been well known in oceanographic community that fluctuations in the marine light field are dominated by the variability of the air-sea interface [25].

In our model we assume that the surface waves are assembled from many linear waves generated by wind over an area much larger than the correlation length of the waves [17]. Therefore, most important water surface descriptors such as displacement and slope can be represented as normal random variables. Experimental measurements of surface-wave statistics confirmed that water surface descriptors have Gaussian distributions. Mastin et al. [9] introduced this long known surface wave synthesis [16] that is based on the sum of sinusoidal amplitudes and phases based on empirical observations of oceans to the computer graphics community. As the heart of our wave generation approach has been described elsewhere [9, 22] we omit most of the details. The height of the water surface at the location $\vec{\mathbf{x}}$ on the grid and time t is

$$\eta(\vec{\mathbf{x}}, t) = \sum_{\vec{\mathbf{k}}} \hat{\eta}(\vec{\mathbf{k}}, t) e^{i\vec{\mathbf{k}}\vec{\mathbf{x}}} \qquad (1)$$

where $\vec{\mathbf{k}}$ is wave vector pointing in a direction of travel of the wave, and $\hat{\eta}(\vec{\mathbf{k}}, t)$ is the Fourier component of the water surface. It is important to mention that we use the *Joint North Sea Wave Project* or the *JONSWAP* spectrum [4]. The advantages of using the JONSWAP spectrum are the simplicity of use and ability to fine tune the model. The only necessary parameter to the model is wind velocity. However, it also enables an advanced user to fine tune the model as some of the parameters (invisible to most users) can be fitted to measured and observed data for both oceans and lakes. Some of the more advanced parameters are available in [25] and [27].

2.1. Whitecaps and foam

The wave generation model described thus far has omitted the effect of whitecaps and foam, which are present at wind speeds greater than a few meters per second. *Whitecaps* are the foamy part of actively breaking waves. The total foam area depends on the temperature difference between the air and the water and on water chemistry.

K_d	diffuse attenuation coefficient for E_d
$K(\theta, \phi)$	diffuse attenuation coefficient
E_d	downwelling radiance
E_u	upwelling radiance
R	total path length
c	beam attenuation coefficient
z	water depth
L_*	in-scattered radiance
a	absorption coefficient
b	total scattering coefficient
b_b	backscattering coefficient
t	water turbidity
$L(sky)$	sky radiance
$L(sun)$	sun radiance

Table 1. Important terms used in the paper

The proper treatment of foam and whitecaps is very difficult [12], but some crude approximations can be made. Let f be the fractional area of the wind-blown water surface that is covered by foam. Monahan presents the following empirical formula [12]:

$$f = 1.59 * 10^{-5} U^{2.55} exp[0.0861(T_w - T_a)], \qquad (2)$$

where U is wind speed, and T_w and T_a are the water and air temperatures in degrees Celsius. We use equation 2 to determine the fraction of water covered by foam that modifies optical properties on the water's surface.

3. Light Transport

To generate realistic images of natural waters one must consider in some detail the interaction of light with the water body. In this section we will split this process into two major parts: events on the surface and light transport inside the water volume. Throughout the discussion we will assume that the viewpoint lies above the surface. This is done only for convenience (for example, we do not need to explicitly take into account n^2 law for radiance) and all the results with minor modifications are applicable to the more general case.

3.1. Across the Surface

We treat water surface as a collection of locally planar facets and deal with light transport across a flat surface in a standard way. If a ray strikes a surface, it is split into reflected and transmitted (refracted) rays. Direction of the refracted ray is given by Snell's law $n_i \sin\theta_i = n_t \sin\theta_t$ where θ_i and θ_t are angles with the facet normal for incident and transmitted rays, respectively and n_i, n_t are real indices of refraction for the corresponding media. We set $n = 1$ and $n = 4/3$ for air and water respectively and ignore the slight dependence of these quantities on the wavelength of light. Snell's law shows that for a sufficiently oblique ray going from water to air it is possible to have total internal reflection when only reflected ray is present. This effect has to be checked for explicitly by the rendering software.

Reflectance and transmittance coefficients can be found from Fresnel formulae. Our rendering system uses full Fresnel expressions which can be found in any standard optics text, but a highly efficient and accurate approximation by Schlick is also available [20].

3.2. Within the Water

Once photons from the sun and the sky pass through the air-water surface, they initiate a complex chain of scattering and absorption events within the water body. The behavior of radiance within natural water bodies is governed by the *radiance transfer equation*, a complex integro-differential equation which expresses changes in radiance along a path inside a water volume through the radiance itself and a number of water optical parameters. The task of finding radiance at a given point inside water body is therefore a prime example of the well known participating media problem, one of the hardest problems in computer graphics. A brute force approach to solving this problem for a large water volume would require enormous amount of computation. Perhaps even more discouraging is the fact that values of optical parameters of natural waters are not easily obtainable with the precision needed for these computations. It is hard to justify computation of the final answer with one percent accuracy if the input data have an error of ten or twenty percent. Furthermore, optical properties of natural waters vary dramatically from open ocean to coastal waters to turbid harbor and even if accurate data are available for some conditions, they will be of no use in a different setting.

All this suggests an approach to the light transport problem which we briefly present now. Due to space limitations we can not go into the details of marine optics which are needed to justify the simplification we made or derive some of the equations we use (for example, equations 4 or 7). Interested readers are referred to two classic texts [6, 11]. If extreme detail is desired, the six volume treatise of Preisendorfer [19] is ideal. The sheer volume of the Preisendorfer's volumes testify to the complexity of the subject.

First, we simplify the problem by assuming the existence of two separate but related underwater light fields: the diffuse field radiance L_{df} due to combined effect of light scattered throughout the media and the directional radiance L which behavior we are ultimately interested in for rendering. We assume a uniform water body so that all optical properties are constant throughout. We will also adopt the

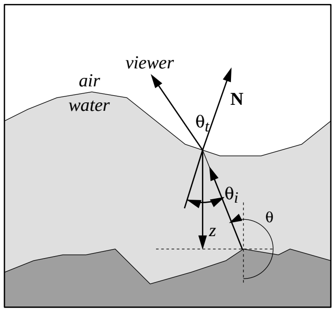

Figure 2. *Geometry of light transport. The propagation angle θ is counted from vertical "down" direction and for the geometry shown exceeds 180 degrees.*

standard marine optics system of notation on figure 2 with positive z-axis pointing down and angle θ to the propagating ray counted from this direction.

The change with depth of the diffuse radiance L propagating in direction (θ, ϕ) is given by

$$\frac{dL_{df}(z,\theta,\phi)}{dr} = -K(\theta,\phi)L_{df}(z,\theta,\phi)\cos\theta \qquad (3)$$

where $K(\theta, \phi)$ is the *diffuse attenuation coefficient for radiance* in a given direction, z is the depth and $dr = -dz/\cos\theta$ is the differential path length which is always positive. This equation is the definition of the diffuse attenuation coefficient and comes directly from experimental observations. On the other hand, change in radiance is due to two separate physical effects: losses from attenuation and gain from in-scattering:

$$\frac{dL_{df}(z,\theta,\phi)}{dr} = -cL_{df}(z,\theta,\phi) + L_*(z,\theta,\phi) \qquad (4)$$

where c is *beam attenuation coefficient* and L_* is in-scattered radiance. Analogous equation holds for directional radiance:

$$\frac{dL(z,\theta,\phi)}{dr} = -cL(z,\theta,\phi) + L_*(z,\theta,\phi) \qquad (5)$$

Experimental evidences suggest that $K(\theta, \phi)$ is often independent of direction and moreover, its numerical value is very close to another coefficient which is much easier measured and for which numerical values, as a consequence, are much more readily available. This quantity is K_d, the *diffuse attenuation coefficient for downwelling radiance*. Using this fact and integrating the combination of the last three equations over the entire path of sight we obtain the final expression

$$L(0,\theta,\phi) = L(z,\theta,\phi)e^{-cR} + L_{df}(0)(1 - e^{(-c+K_d\cos\theta)R}) \qquad (6)$$

This equation gives apparent radiance just below the air-water interface $L(0)$ of the target at depth z having its own radiance $L(z)$. Here $R = -z/\cos\theta$ is the total path length and $L_{df}(0)$ is the diffuse radiance just below the sea surface which we will estimate below. This equation is a special case of a more general expression relating radiances at two arbitrary depths which can be obtained through the same procedure using different initial conditions in integration. Also note that according to our convention $\cos\theta$ is negative while all other values in equation 6 are positive. To estimate $L_{df}(0)$ we assume that radiance going upwards consists only of uniform diffuse light and use a well known relation between upwelling $E_u = \int_{\Omega_{up}} L\cos\theta d\Omega$ and downwelling $E_d = \int_{\Omega_{down}} L\cos\theta d\Omega$ radiances using *irradiance ratio* S:

$$L_{df}(0) = \frac{E_u(0)}{\pi} = \frac{SE_d(0)}{\pi} \approx \frac{0.33b_b}{a}(\frac{E_d(0)}{\pi}) \qquad (7)$$

where we introduced new water optical parameters: backscattering coefficient b_b and absorption coefficient a. $E_d(0)$ is the downwelling irradiance just below the surface which can be approximated as a sum of sun and sky contributions: $E_d(0) = \pi L(sky) + L(sun)\cos\theta_{sun}$. We now have everything we need to perform light transport calculations once we know parameters b_b, a, c and K_d. Important terms are summarized in Table 1.

3.3. Optical Parameter Estimation

For a general case, all four optical parameters we need are independent from each other and we have to find measured or computed values for all of them separately. Moreover, to get the color of water right, we need the four optical parameters to vary with wavelength. Although theoretical models for these parameters do exist, they are quite complicated and, in turn, rely on even less readily available characteristics, such as scattering functions, phytoplankton concentrations, etc. Fortunately, a much simpler classification of natural waters exists. Jerlov [6] suggested a classification based on coefficient $K_d(\lambda)$, experimental measurements of which over the entire visible spectrum for a given water type are available from many sources, for example [6], [11], and [1]. He introduced twelve water types and assigned a particular $K_d(\lambda)$ spectrum to each of them. These spectra are the only fully wavelength dependent input data required by our model. We will also use single wavelength values for the total scattering coefficient b provided for a given water type in references [11] or [23].

3.4. Simplifying the parameters

A naturally clear water, may look cloudy or muddy due to particles of matter suspended in it. This cloudy appearance is called *turbidity*. Turbidity affects the penetration of sunlight into a body of water. Algae and suspended particles of silt, plant fibers, sawdust, chemicals, and microorganisms are some of the causes of turbidity in water. We now introduce a single cumulative turbidity parameter t we call which assumes intuitive values in the interval from zero for clearest open ocean waters to one for very turbid harbor conditions. This parameter is used to obtain spectral data $K_d(\lambda)$ and single number for b by interpolation of the input data. We then use simple approximate relations among water optical parameters to obtain all the other coefficients. Much more accurate (and complicated) relations are available from the literature, but the simplest versions suffice for our purposes.

First of all, we obtain $a(\lambda) \approx K_d$ [5]. Second, from the single $b(\lambda_0)$ we get $b(\lambda)$ and then $b_b(\lambda)$ using very recently established [7] experimental relations

$$b(\lambda) = b(\lambda_0)\frac{m\lambda + i}{m\lambda_0 + i} \quad (8)$$

where $m = -0.00113$, $i = 1.62517$ and $b_b(\lambda) = 0.01829b(\lambda) + 0.00006$. Finally, we use the definition $c(\lambda) = a(\lambda) + b_b(\lambda)$.

Our use of the turbidity parameter t is similar in spirit to that of Preetham et al. [18]. To make our model more useful in practice we are currently working on a simple way to obtain $K_d(\lambda)$ from t. Preliminary results suggest that we can obtain CIE chromaticity values for the transmittance per meter of water $T(\lambda)$ (related to $K_d(\lambda)$ as $T = \exp(-K_d(\lambda))$) by a simple relation $x = 0.291 + 0.054t$, $y = 0.321 + 0.064t$, then obtain spectral data by using one of many chromaticity conversion procedures and finally normalize the integrated spectra over wavelength transmittance so that it matches the average transmittance of the desired water type.

4. Discussion and Future Work

We have presented a method for wave generation and light transport in natural waters. The method uses a few simple and physically meaningful parameters that control both wave generation as well as the appearance of water bodies. Color plate shows renderings produced for oceans with different water types (deep water, muddy coastal water and tropical water). Figure 3 shows how the color of the water changes with depth. Effects like this can often be observed in lakes and tropical islands. Figure 5 demonstrates that in order to make realistic images of water atmospheric conditions and illumination has to be computed accurately in addition to proper handling of wave generation and light transport in the water body. Figure 4 shows the same scene with different atmospheric conditions. Whitecaps can be seen during the stormy and rainy conditions (also Color Plate). Figure 6 shows fresh water lake Crater Lake – a lake in volcanic caldera.

All images were generated using direct interpolation $K_d(\lambda)$ of experimental data provided in [11] and [23]. Preliminary results show that equally compelling images can be produced using simple and intuitive turbidity parameter and procedure described in Section 3.4.

The water surface mesh and water type was input to a Monte Carlo path tracer [8] with a sky model similar to that used by Preetham et al. [18] that appropriately controls illumination based on time/date/place. We model clouds procedurally using an approach similar to [2] — instead of points we use a turbulence function to control the placement of the clouds. Glare effects were added in post-processing step using similar technique as [21].

Although this work showed some promising results there are many improvements needed to render and animate water. Breaking waves, wakes, and splashing cannot be rendered with the described method. Whitecaps and foam are not very well integrated into the wave generation. Furthermore, underwater sunbeams cannot be rendered due to global nature of the effect. On the other hand, the method can easily be extended to accommodate caustics on underwater surfaces with some preprocessing and caustic image generation. Although the water waves can be animated, there are several difficulties when animation is concerned. Water has drastically different behavior at different scales. Water does not scale well because surface tension has different characteristics depending on scale. Animating objects in water and getting realistic motion is extremely difficult task. Complex fluid dynamics is presently beyond realistic use due to the complexity of the phenomena and prohibitive computational costs.

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Figure 3. *Shallow water in the tropics*

Figure 4. *Different atmospheric conditions and whitecaps*

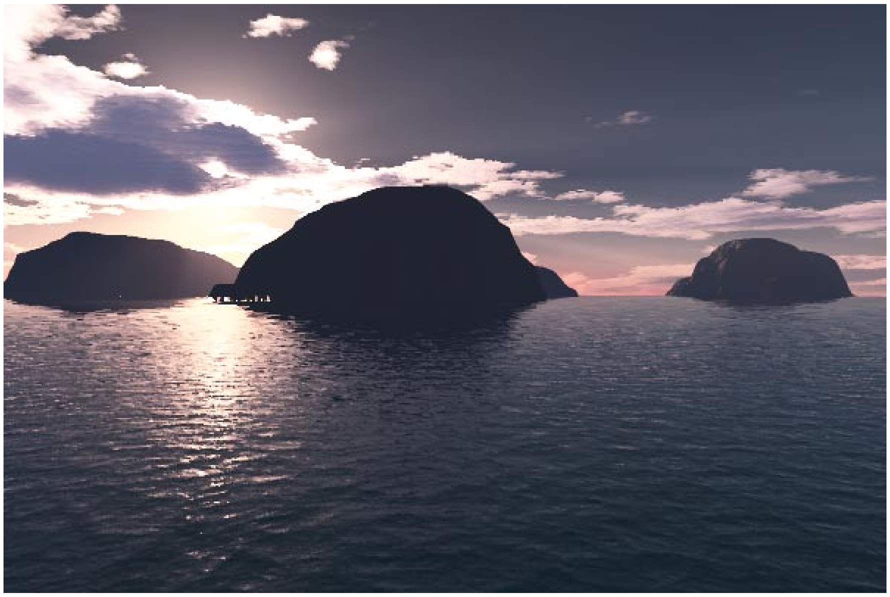

Figure 5. *Island at sunset*

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Figure 6. *Crater Lake – fresh water lake in Oregon.*