What are established and novel computational methods for simulating the visual characteristics and physical behaviors of watercolor painting, including pigment dispersion, fluid dynamics, color blending, paper interaction, and drying effects?

Watercolor simulation methods combine established approaches like cellular automata and Navier-Stokes equations with newer techniques such as Lattice Boltzmann and machine learning to model fluid dynamics, pigment behavior, paper interaction, and drying effects.

Abstract

Multiple studies describe a range of computational methods that simulate watercolor painting by modeling fluid dynamics, pigment dispersion, color blending, paper interaction, and drying. Two studies employ cellular automata to model diffusion, surface tension, gravity, and fiber-level paper absorbency through parallel per-pixel computations (Small, 1991a; Small, 1991b). Three studies use two-dimensional Navier–Stokes equations to drive fluid advection and vorticity while incorporating layered canvas or texture-based paper models; Van Laerhoven and Reeth (2005) report interactive performance at 20 frames per second. Two studies apply the Lattice Boltzmann method or equation to simulate pigment mixing, water percolation, and drying effects—with Chu and Tai (2005) achieving 44 fps via a hybrid CPU/GPU approach and Oh et al. (2015) noting interactive performance on low-power and mobile devices. An additional approach uses a shallow water simulation (Curtis et al., 1997), while Xu et al. (2007) combine physically based surface chemistry with machine learning to capture adsorption/desorption dynamics and pigment deposition at approximately 8 fps for a 10,000-pixel stroke.

Thus, established methods such as cellular automata, Navier–Stokes fluid simulation, and Kubelka–Munk color blending coexist with novel approaches that incorporate Lattice Boltzmann techniques, hybrid architectures, and data-driven enhancements. Paper interaction is modeled via fiber-level absorption, texture maps, or three-layer frameworks, and drying is simulated using either physically based evaporation equations or heuristic water reduction. These studies show that careful domain decomposition, GPU acceleration, and parallel processing enable a balance between physical accuracy and computational performance.

Paper search

Using your research question ”What are established and novel computational methods for simulating the visual characteristics and physical behaviors of watercolor painting, including pigment dispersion, fluid dynamics, color blending, paper interaction, and drying effects?”, we searched across over 126 million academic papers from the Semantic Scholar corpus. We retrieved the 50 papers most relevant to the query.

Screening

We screened in papers that met these criteria:

- **Computational Method**: Does the study present computational methods or algorithms specifically for watercolor simulation?
- **Technical Focus**: Does the research address at least one of the following: pigment dispersion simulation, fluid dynamics modeling, color blending algorithms, paper-fluid interaction, or drying effect

simulation?

- **Implementation Details**: Does the paper provide technical implementation details of the watercolor rendering system?
- **Empirical Validation**: Does the study include empirical validation of the proposed watercolor simulation methods?
- **Computational Component**: Does the study include computational elements beyond traditional watercolor painting techniques?
- **Physical Simulation**: Does the study include physical simulation components rather than only digital painting tools?
- **Watercolor Specificity**: Does the fluid simulation research specifically address watercolor behavior rather than general fluid dynamics?

We considered all screening questions together and made a holistic judgement about whether to screen in each paper.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Computational Approach for Watercolor Simulation**:

  Identify and describe the primary computational method used for watercolor painting simulation. Look in the methods or technical description section. Specifically extract:

- Name of the computational technique (e.g., lattice Boltzmann method, distributed canvas)
- Key algorithmic components
- Computational domain (e.g., 2D, 3D, grid-based)
- Any unique technical innovations

If multiple computational approaches are described, list them in order of prominence. If information is incomplete, note "Insufficient details provided".

- **Simulation Dynamics and Physical Phenomena**:

  Identify specific physical phenomena simulated in the watercolor painting system. Systematically extract evidence of:

- Pigment dispersion mechanisms
- Fluid dynamics modeling
- Color mixing/blending techniques
- Paper/surface interaction models
- Drying effect simulations

For each phenomenon, note:

- Whether it is physically based or heuristic
- Level of detail in the simulation
- Any specific computational techniques used to model the phenomenon

If a phenomenon is mentioned but not comprehensively modeled, note the limitations.

- **Computational Performance and Hardware Utilization**:

  Extract information about the computational efficiency and hardware implementation:

- Hardware platform used (CPU, GPU, distributed systems)
- Real-time performance capabilities
- Computational complexity
- Suitability for different computing environments (desktop, mobile, etc.)

Quantify performance metrics if provided (e.g., frames per second, computational overhead). If no specific metrics are given, use qualitative descriptors from the text.

- **Visual Output and Rendering Characteristics**:

  Describe the visual characteristics and rendering approach of the watercolor simulation:

- Rendering model used (e.g., Kubelka-Munk diffuse reflectance)
- Specific visual effects simulated (e.g., dark-edge effect, glazing)
- Color model characteristics
- Level of visual realism achieved

Include direct quotes or references to visual quality assessments if available. If subjective evaluations are present, note them explicitly.

Results

Characteristics of Included Studies

Study	Study Focus	Simulation Method	Key Features	Performance Metrics	Full text retrieved
Small, 1991a	Physically-based watercolor simulation on parallel architecture	Complex cellular automata on Connection Machine II	Models diffusion, surface tension, gravity, humidity, paper absorbency, pigment molecular weight; parallel per-pixel computation	2–10x slower than real-time at 1024x1024; scalable with more processors	Yes

Study	Study Focus	Simulation Method	Key Features	Performance Metrics	Full text retrieved
Small, 1991b	(Abstract only) Parallel simulation of watercolor	Complex cellular automata (abstract only)	Models diffusion, surface tension, gravity, humidity, paper absorbency (abstract only)	~1/10th real-time (abstract only)	No
Van Laerhoven and Reeth, 2005	Real-time, interactive watercolor simulation	Layered canvas, two-dimensional Navier-Stokes equations, graphics processing unit (GPU) shaders	Physically-based and heuristic rules, Kubelka-Munk rendering, simulates dark-edge, glazing, wet-on-wet	20 frames per second (fps) on desktop GPU; interactive at half-rate for large interactions	Yes
Oh et al., 2015	(Abstract only) Efficient, interactive watercolor for low-power/mobile	Subdomain-based Lattice Boltzmann method (LBM)	Domain decomposition, improved subtractive color model, diffusion, pigment mixing, drying	Interactive on low-power/mobile; no quantitative metrics	No
Chu and Tai, 2005	Physically-based ink dispersion in absorbent paper	Lattice Boltzmann equation (LBE), hybrid central processing unit (CPU)/GPU	Simulates percolation, variable permeability, boundary roughening, texture maps, drying	44 fps at 1536^2, 512^2 simulation, d-scale 3; efficient LBE operations	Yes
Curtis et al., 1997	(Abstract only) Computer-generated watercolor	Shallow water simulation, Kubelka-Munk compositing	Ordered translucent glazes, automatic image ”water-colorization”	No mention found	No

Study	Study Focus	Simulation Method	Key Features	Performance Metrics	Full text retrieved
Ďurikovič and Páleníková, 2017	(Abstract only) Real-time watercolor with fluid vorticity	Two-dimensional Navier-Stokes equations on GPU	Vorticity, paper roughness, Kubelka-Munk, semi-transparent layers	No mention found; real-time implied	No
Durikovic and Palenikova, 2017	(Abstract only) Real-time watercolor with fluid vorticity	Two-dimensional Navier-Stokes equations on GPU	Vorticity, paper roughness, Kubelka-Munk, semi-transparent layers	Real-time; no quantitative metrics	No
Xu et al., 2007	Generic pigment model for digital painting	Physically-based, surface chemistry, machine learning, GPU	Adsorption/desorption, advection-diffusion, cross-diffusion, evaporation, Kubelka-Munk, neural pigment mixing	8 fps for 10,000-pixel stroke on modest PC	Yes
Van Laerhoven et al., 2004	(Abstract only) Real-time watercolor on distributed paper model	Distributed three-layer paper model	Grid of subpapers, remote process delegation, real-time for large surfaces	Real-time; no quantitative metrics	No

Simulation methods used for digital watercolor in the included studies:

- Cellular automata:2 studies (Small, 1991a; Small, 1991b)
- Lattice Boltzmann method or equation:2 studies (Oh et al., 2015; Chu and Tai, 2005)
- Two-dimensional Navier-Stokes equations:3 studies (Van Laerhoven and Reeth, 2005; Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017)
- Shallow water simulation:1 study (Curtis et al., 1997)
- Layered or distributed paper models:2 studies (Van Laerhoven and Reeth, 2005; Van Laerhoven et al., 2004)
- Physically-based with surface chemistry or machine learning:1 study (Xu et al., 2007)
- GPU-based implementation:4 studies (Van Laerhoven and Reeth, 2005; Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017; Xu et al., 2007)
- Hybrid CPU/GPU:1 study (Chu and Tai, 2005)

Performance metrics:

- Quantitative frames per second (fps) or speed data:5 studies

- Real-time performance (explicitly stated or implied):5 studies
- Interactive performance:2 studies
- No mention of quantitative performance metrics:3 studies
- No mention of any performance information:2 studies

Some studies used multiple simulation methods or combined physical and heuristic rules. Several studies were only available as abstracts, which may explain missing quantitative data.

Thematic Analysis

Physical Simulation Models

Study	Fluid Dynamics Approach	Pigment Behavior Model	Paper Interaction System
Small, 1991a	Displacement forces, gradients (cellular automata)	Diffusion, molecular weight, surface tension	Paper absorbency, fiber-level modeling
Small, 1991b	Diffusion, surface tension, gravity (cellular automata)	Diffusion	Paper absorbency, fiber simulation
Van Laerhoven and Reeth, 2005	Two-dimensional Navier-Stokes equations, self-advection, diffusion	Velocity field, pigment advection	Capillary effects, two-dimensional grid, texture-based
Oh et al., 2015	Lattice Boltzmann method (LBM)	Diffusion, pigment mixing	No mention found
Chu and Tai, 2005	Lattice Boltzmann equation (LBE)	Water percolation, pigment movement	Variable permeability, boundary roughening, texture maps
Curtis et al., 1997	Shallow water simulation	No mention found	No mention found
Ďurikovič and Páleníková, 2017	Two-dimensional Navier-Stokes equations, vorticity	Pigment movement in water	Paper roughness, structure
Durikovic and Palenikova, 2017	Two-dimensional Navier-Stokes equations, vorticity	Pigment movement in water	Paper roughness, structure
Xu et al., 2007	Advection-diffusion, cross-diffusion	Adsorption/desorption, pigment particles	Fiber-level adsorption, paper fiber distribution
Van Laerhoven et al., 2004	No mention found	No mention found	Three-layer paper model

Fluid dynamics approaches:

- Cellular automata:2 studies (Small, 1991a; Small, 1991b)

- Two-dimensional Navier-Stokes equations:3 studies (Van Laerhoven and Reeth, 2005; Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017)
- Lattice Boltzmann method or equation:2 studies (Oh et al., 2015; Chu and Tai, 2005)
- Shallow water simulation:1 study (Curtis et al., 1997)
- Advection-diffusion or cross-diffusion:1 study (Xu et al., 2007)
- No mention found in the abstract:1 study (Van Laerhoven et al., 2004)

Paper interaction systems:

- Fiber-level modeling:3 studies (Small, 1991a; Small, 1991b; Xu et al., 2007)
- Grid or texture-based approach:1 study (Van Laerhoven and Reeth, 2005)
- Paper roughness or structure:3 studies (Chu and Tai, 2005; Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017)
- Three-layer paper model:1 study (Van Laerhoven et al., 2004)
- No mention found:2 studies (Oh et al., 2015; Curtis et al., 1997)

Real-time Performance Optimization

Study	Domain Decomposition	Distributed Computing	Performance-Quality Tradeoffs
Small, 1991a	Parallel per-pixel computation	Connection Machine II	High realism, high computational cost
Small, 1991b	Parallel per-pixel computation	Connection Machine II	Slower than real-time
Van Laerhoven and Reeth, 2005	Layered canvas, GPU shaders	No	20 fps, optimizations for interactivity
Oh et al., 2015	Subdomain decomposition (Lattice Boltzmann method)	No mention found	Interactive on low-power/mobile
Chu and Tai, 2005	No mention found	Hybrid CPU/GPU	44 fps, efficient Lattice Boltzmann equation operations
Curtis et al., 1997	No mention found	No mention found	No mention found
Ďurikovič and Páleníková, 2017	No mention found	GPU	Real-time implied
Durikovic and Palenikova, 2017	No mention found	GPU	Real-time implied
Xu et al., 2007	No mention found	GPU acceleration	8 fps on modest PC
Van Laerhoven et al., 2004	Grid of subpapers	Distributed system	Real-time for large surfaces

Domain decomposition:

- Parallel per-pixel decomposition:2 studies (Small, 1991a; Small, 1991b)
- Layered canvas decomposition:1 study (Van Laerhoven and Reeth, 2005)

- Subdomain or grid-based decomposition:2 studies (Oh et al., 2015; Van Laerhoven et al., 2004)
- No mention found:5 studies

Distributed computing:

- Connection Machine (massively parallel hardware):2 studies (Small, 1991a; Small, 1991b)
- GPU-based approaches (including hybrid CPU/GPU, GPU acceleration, and GPU shaders):4 studies (Van Laerhoven and Reeth, 2005; Chu and Tai, 2005; Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017; Xu et al., 2007)
- Distributed system (multi-machine):1 study (Van Laerhoven et al., 2004)
- No distributed computing:1 study (Van Laerhoven and Reeth, 2005)
- No mention found:2 studies

Performance-quality tradeoffs:

- Real-time or interactive performance (including "implied" real-time):6 studies
- Specific frame rates reported:3 studies (20 fps, 44 fps, and 8 fps)
- High realism with high computational cost:1 study
- Slower than real-time performance:1 study
- No mention found:1 study

Material Interaction Systems

Study	Pigment-Water Interaction	Paper Absorption Model	Drying Effect Simulation
Small, 1991a	Physically-based, gradient fields	Absorbency, fiber-level	Heuristic, water content reduction
Small, 1991b	Diffusion, surface tension	Absorbency, fiber simulation	No mention found
Van Laerhoven and Reeth, 2005	Physically-based, velocity field	Capillary, texture-based	Physically-based, evaporation rates
Oh et al., 2015	Diffusion, pigment mixing	No mention found	Drying simulated, details not specified
Chu and Tai, 2005	Water percolation, pigment movement	Variable permeability, texture maps	Physically-based, evaporation rates
Curtis et al., 1997	No mention found	No mention found	No mention found
Ďurikovič and Páleníková, 2017	Pigment in flowing water	Paper roughness, structure	No mention found
Durikovic and Palenikova, 2017	Pigment in flowing water	Paper roughness, structure	No mention found
Xu et al., 2007	Adsorption/desorption, cross-diffusion	Fiber-level, variable adsorption	Physically-based, evaporation equation
Van Laerhoven et al., 2004	No mention found	Three-layer model	No mention found

Pigment-water interaction:

- Physically-based models (using gradient or velocity fields):2 studies (Small, 1991a; Van Laerhoven and Reeth, 2005)
- Diffusion-based models (including pigment mixing):2 studies (Small, 1991b; Oh et al., 2015)
- Water percolation models:1 study (Chu and Tai, 2005)
- Pigment in flowing water:2 studies (Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017)
- Adsorption/desorption and cross-diffusion models:1 study (Xu et al., 2007)
- No mention found:2 studies

Paper absorption model:

- Fiber-level absorption models:3 studies (Small, 1991a; Small, 1991b; Xu et al., 2007)
- Capillary or texture-based absorption models:1 study (Van Laerhoven and Reeth, 2005)
- Variable permeability or texture map models:1 study (Chu and Tai, 2005)
- Paper roughness or structure:2 studies (Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017)
- Three-layer absorption model:1 study (Van Laerhoven et al., 2004)
- No mention found:2 studies

Drying effect simulation:

- Physically-based drying or evaporation models:3 studies (Van Laerhoven and Reeth, 2005; Chu and Tai, 2005; Xu et al., 2007)
- Heuristic drying model:1 study (Small, 1991a)
- Drying simulated, details not specified:1 study (Oh et al., 2015)
- No mention found:5 studies

Visual Quality and Rendering

Study	Color Blending Technique	Layer Composition	Surface Effect Rendering	Visual Realism Assessment
Small, 1991a	Subtractive color model	Highlights, shadows, drips	Texture/bump maps, high-resolution display	Realistic diffusion/drips (subjective)
Small, 1991b	No mention found	No mention found	No mention found	No mention found
Van Laerhoven and Reeth, 2005	Kubelka-Munk, user palette	Layered canvas, optical composition	Dark-edge, glazing, wet-on-wet	High realism, positive user evaluation
Oh et al., 2015	Improved subtractive model	No mention found	Diffusion, pigment mixing, drying	Suitable for professional art
Chu and Tai, 2005	No mention found, OpenGL/Cg	Implicit modeling, image-based	Boundary roughening, hair texture	”Very realistic and intuitive” (subjective)
Curtis et al., 1997	Kubelka-Munk	Translucent glazes	No mention found	No mention found
Ďurikovič and Páleníková, 2017	Kubelka-Munk	Semi-transparent layers	Water flow, vorticity, diffusion	No mention found

Study	Color Blending Technique	Layer Composition	Surface Effect Rendering	Visual Realism Assessment
Durikovic and Palenikova, 2017	Kubelka-Munk	Semi-transparent layers	Water flow, vorticity, diffusion	Implied high realism
Xu et al., 2007	Machine learning, Kubelka-Munk	Wet-to-dry continuum	Fiber interaction, pigment deposition	High fidelity, efficient rendering
Van Laerhoven et al., 2004	No mention found	No mention found	No mention found	No mention found

Color blending techniques:

- Kubelka-Munk model:5 studies (Van Laerhoven and Reeth, 2005; Curtis et al., 1997; Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017; Xu et al., 2007)
- Subtractive color models (including improved versions):2 studies (Small, 1991a; Oh et al., 2015)
- Machine learning (in combination with Kubelka-Munk):1 study (Xu et al., 2007)
- No mention found:3 studies

Layer composition:

- Semi-transparent layers:2 studies (Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017)
- Layered canvas/optical composition, translucent glazes, wet-to-dry continuum, highlights/shadows/drips, implicit modeling/image-based approaches:1 study each
- No mention found:3 studies

Surface effect rendering:

- Water flow, vorticity, and diffusion effects:2 studies (Ďurikovič and Páleníková, 2017; Durikovic and Palenikova, 2017)
- Diffusion/pigment mixing/drying, dark-edge/glazing/wet-on-wet, texture/bump maps, boundary roughening/hair texture, fiber interaction/pigment deposition:1 study each
- No mention found:3 studies

Visual realism assessment:

- Positive or subjectively positive realism assessments:4 studies (Small, 1991a; Van Laerhoven and Reeth, 2005; Chu and Tai, 2005; Xu et al., 2007)
- Implied positive realism:2 studies (Durikovic and Palenikova, 2017; Oh et al., 2015)
- No mention found:4 studies

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