ARTICLE CASE

The Spatially Explicit Water Footprint of Blue Jeans: Spatial Methods in Action for Sustainable Consumer Products and Corporate Management of Water

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ABSTRACT To improve and to protect brand reputation, corporate sustainability officers must assist with decisions about how to manage supply chains to avoid deleterious impacts from consumer products, such as food or clothing. This case study shows how one method typically used to identify problematic materials and sources in a supply chain, life cycle assessment, can be made spatially explicit for water footprints. Water must be understood spatially because the use of the same amount of water in an arid place creates more ecological damage than the use of water in places with ample water resources. This case reports on the development of a spatially explicit water footprint for Guess?, Inc., a global apparel company to highlight "hot spots" of negative impacts on water resources. Freshwater resources consumed throughout the life cycle for a pair of blue jeans were assessed, including the growth of cotton, production of the fabric and other materials, industrial laundering, and washing by the consumer. The locations of these steps were then mapped with a geographic information system to generate spatially explicit water impact estimates. Engaging with this case, students will learn about key methodological choices and limitations in such projects, think about how to advise the company on steps to be taken in its water management action plan, and reflect on the implications for sustainable corporate management of consumer products.

INTRODUCTION

Scarcity of freshwater is a major global sustainability problem that primarily affects arid places, and particularly those that are also impoverished [1]. Due to a lack of surface water in catchment basins and/or depleted groundwater reserves, places with the physical scarcity of freshwater often experience constraints on development and damage to ecosystems. Although scarcity may also result from economic and political conditions even when water is available [2], examining physical scarcity provides a starting point to understand the impacts of spatial variation in scarcity in a globalized world. When water-intensive consumer products are produced in arid places and shipped to global consumer markets, the burdens of making the products fall on these arid places.

This case reports on data and methods that were used to help Guess?, Inc., a major global apparel company and lifestyle brand, to understand how water use at various places at different stages of production affects the impacts from its denim. A spatially explicit analysis of denim in the Guess?, Inc. supply chain is used to calculate the total water used in producing and wearing a representative pair of blue jeans sold by the company, what I term its "spatially explicit water footprint." This case also points out "hot spots" as places in the supply chain where physical scarcity of water intersects with water-intensive processes of production to impact surface and groundwater resources.

Production of consumer goods, and the raw materials and components from which they are made, occurs around the world at different locations with varying levels of water availability. Since the 1970s with a marked acceleration in the 1980s and 1990s, the system of production globalized in a form known as "post-Fordist" production [3, 4]. This resulted in globally dispersed supply chains with many links among a diverse set of large and small producers [5]. The apparel industry is representative of this

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shift as the same textiles, and eventually a diverse array of finished garments, is often flexibly sourced from a large number of large and small producers across the world [6].

Like most of the apparel industry, Guess?, Inc. has a complex global supply chain, including thousands of individual products and hundreds of suppliers. The apparel sector is under social pressure, including direct pressure from consumers and investors, in the case of publicly held companies, to develop meaningful programs of corporate social responsibility [7]. For example, the United Nation's Environment Programme describes apparel and fashion as a major opportunity for improving sustainability both on water and climate change, estimating that the apparel industry is responsible for 8% of global warming impacts across the life cycle of its products [8].

For transparency in environmental performance, companies like Guess?, Inc. often employ sustainability professionals, including technical consultants, to estimate carbon or water footprints for operations or products according to voluntary protocols, typically using methods and datasets from environmental life cycle assessment (LCA) experts [7, 9]. Such studies have many purposes, including highlighting areas where companies face reputational and future regulatory or financial risk, and also especially in the case of water footprints, highlighting vulnerabilities in the supply chain due to disruptions in physical availability of water from on-going climate change [10].

My role in this case was as a paid technical consultant to Guess?, Inc. In a series of discussions, I collaborated primarily with Jaclyn Allen, the Director of Corporate Sustainability at Guess?, Inc., to identify the extent to which supply chain data could be used to understand the spatial variation of the water footprint of denim in Guess?, Inc. products. Throughout this case study, I use the pronoun "we" to reference this collaboration, which included assistance with obtaining data and insights on the company's products and supply chain from several departments across the company. Before I was retained, we discussed and selected the method described in the case. Within the constraints of feasibility, as described at certain points in the case, our goal was to bring the latest methods for determining water impacts to bear on analyzing the company's supply chain.

Like other consumer products companies, apparel companies face deep challenges to ensure environmental and social responsibility across large, diverse, and globalized supply chains. In the case of carbon and water footprints, the typical practice of predominant methods like LCAs, as described in the case, often ignore how space and place affect the accounting of impacts. This is especially true for commodities that are hard to track back to their source [11, 12]. This case aims to help students understand and practice analysis that accounts for variation in space and place in assessing impacts in the consumer products sector.

CASE EXAMINATION

There is a significant debate over the methods used to account for environmental impacts in consumer products, and this is especially true for measuring spatial variation in impacts and impacts from the use of freshwater [13]. Two competing methods are in use to measure the impacts of freshwater in consumer products: LCA and water footprint assessment (WFA). LCA attempts to measure the impacts of a product system from "cradle to grave," including all the major steps of production for multiple environmental indicators. WFA is a method that specializes in measuring the consumption of water in making products, and it generally considers steps of production only up to the delivery to the consumer.

Given the significant debate over the methods and data limitations, my first challenge was to work with Guess?, Inc. to choose an approach. Thus, I start the case examination with a broad section on the selection of the case method. This section compares LCA and WFA methods and explains why I chose a hybrid of the two, labeled a "spatially explicit water footprint." Then, in a second broad section, I explain how I executed this approach for Guess?, Inc. This section includes details on the scope of the water footprint, and how I located production locations by using a sampling scheme to audit company data in conjunction with global trade data. I also report on the calculations and results for the water footprint, and how I mapped and calculated results for the hot spots analysis.

Selection of Case Method: LCA Modeling

LCA modeling is in wide-spread use to estimate various types of environmental impacts considering cradle-to-grave activities in consumer product systems. It is supported by a family of International Organization for Standardization (ISO) standards, the first version of which was published in 1997. There are also standard impact models, and a suite of secondary datasets with pollution and resource consumption data for industrial, mining, energy, transport, and agricultural processes [14, 15].

Typically, LCA measures not only the total impacts of all products or even a single product produced by a company but also a normalized measure suitable for comparison to other like products. In LCA terms, this is called a "functional unit." For example, the functional unit for a pair of blue jeans would be the water required and other impacts created from "one day of wear" of a pair of blue jeans.

Despite its ubiquity in corporate sustainability programs, environmental LCA methods are known to suffer from various limitations, uncertainties, and inaccuracies, which stem from failing to model complex spatial and temporal interactions in technological systems [16]. These should be but are not always disclosed when the method is applied to given product systems [16, 17].

Starting in the early 2000s, the LCA community began to focus on a weakness with serious implications for global consumer products companies: the use of static and site-independent models in LCAs to generalize impacts across multiple locations [18]. This lack of site-specificity is problematic in both of LCA's major methodological phases.

The first phase in LCA is the estimation of raw materials consumption and pollution across all processes from cradle-to-grave, known as the "life cycle inventory." Here, the fundamental issue is that the major secondary datasets that represent such "inventory processes" come from fairly few locations, which are in the majority from Northern Europe (e.g., including proprietary datasets like the major Swiss dataset "Ecoinvent"). Further, although there is a simple denotation of population density in terms of rural vs urban locations, the inventory processes are not geocoded [i.e., they cannot be located as points or polygons on geographic information system (GIS) maps]. Thus, analysts face considerable expense and time in developing primary datasets if they would do spatially explicit analysis.

The second phase in LCA is the estimation of impacts on human health and ecosystems, known as the "life cycle impact assessment." Here, the models generally lack any spatial input data or parameters to represent locations of concentrations of pollutants or damage to land cover that could raise or lower estimated impacts. Once again, one exception is that impact models sometimes denote urban vs rural population densities to estimate the magnitude of human health impacts of pollution.

Since the mid-2000s, limited but important progress has been made in coupling LCA with GISs in studies where primary inventory data have been gathered and geocoded. These studies focus on production systems or technologies that make significant use of land (e.g., biofuels, solar, and agriculture), where inventory estimates may differ greatly depending on the location and type of land used [19, 20]. This approach has become known as "spatially explicit life cycle assessment" [21].

Less progress has been made on the problem of introducing site-specific and dynamic temporal parameters and data into a life cycle impact assessment models. However, one notable effort in this regard was the development in the LCA community of a method to normalize water use in product systems by the degree of surface freshwater availability [22]. The resulting "water stress impact" (WSI) measure scores a product system that uses lots of water in areas with relatively little surface freshwater compared with global averages as more impactful than the opposite case. Before water use values are totaled across processes, they are multiplied by the WSI for each location. The summed result is given in "liters-equivalent" of water to assist with comparisons across product systems. The method has been extended to chains of impacts that result from water stress and applied at the national level to cotton textiles for illustration [22].

Studies of blue jeans and cotton garments have made use of conventional (i.e., *non*-spatially explicit) LCA methods. Levi Strauss and Company famously conducted an LCA for their Levi's 501 jeans product, which estimated several major categories of environmental impacts for various life cycle phases including water consumption figures [23, 24]. One of the world's major LCA consulting firms, PE International, studied the cotton in knit golf shirts and woven casual pants and disclosed results in terms of percentage of impacts for life cycle stages (e.g., raw materials, manufacturing, and use), but not the absolute magnitude of impacts [25, 26]. It can be inferred from the public versions of these LCAs that neither considered differences in water consumption depending on production locations nor reported water impacts using the WSI measure mentioned above.

Selection of Case Method: WFA

In 2011, a method specifically for measuring water footprints was standardized and published by the water footprint network (WFN), a non-governmental organization based in the Netherlands. The WFN provides a global standard for "WFA" that can be used to account for water use in product systems, organizations, or water consumption at the national level [27].

WFAs account for three types of water: green, blue, and dilution (grey) water. In WFA, green water is the water that is added to a product via rainfall, usually in agricultural settings. This water is ignored in LCA, a choice over which there is significant debate [13]. In WFA, blue water is defined as surface water and groundwater that is withdrawn from a watershed and not returned because it is evaporated or incorporated in the product [27]. In WFA, grey water is defined as the water needed to dilute a given quantity of polluted water back to a suitable state for return to the watershed [27]. Again, this type of water is not accounted for in LCA.

Previous studies have used WFA both in studies of cotton and denim. A 2005 study from the WFN uses country-level data on cotton yields and rainfall models to create estimates of blue and green water in cotton production. Estimates were created for the 15-largest cotton-producing countries [28]. The study combines spatial models of agricultural yield with rainfall data in major crop-growing regions within each country to estimate the rainfall and irrigation requirements for growing cotton. This information is then combined with data on the proportion of irrigated cotton production and the harvest yield to give green (rainfall) and blue (irrigated) water consumption estimates per metric ton of cotton production.

The WFN uses their cotton data to report a global average water footprint for a 1,000-g pair of blue jeans (presumably 100% cotton) by adding estimates of fabric processing and finishing derived from a single source from 2000. As is typical in the WFA method, many processes of production are left out (e.g., materials other than cotton and laundries). In LCA terms, the WFA method "truncates" the systems to focus only on what are supposed to be the major impacts (Table 1).

A 2013 study provides a regionally scaled application of the WFA method for the production of denim fabric in three river basins in the southwest area of Spain [29]. The assessment includes not only cotton but also lyocell fiber products sourced from forests that are blended with cotton to form the denim. It developed detailed models of blue, green, and grey water in cotton production in the three river basins, reported as consumed by factories in that region. In the end, it provides spatially and temporally explicit calculations of the water burden of denim production in the three river basins. It focuses on production in only one region, and like most water footprints does not include the use or disposal phase of the product.

The WFA method is spatially explicit in the sense that its datasets account for differences in irrigation of crops, depending on water scarcity and the need for irrigation in various regions. It also provides data and a method that can be used for hot spots analysis, when locations of water consumption in the supply chain can be determined. However, because of the challenge of gathering supply chain data, it is quite rare that hot spots analysis is performed and included in water footprints.

The WFN performed one study that grapples with this issue for C&A apparel, a major apparel retailer that owns multiple brands [30]. The study is similar to the effort here in that it traces cotton throughout C&A's supply chain to places of origin, calculates a water footprint, and then overlays WFN's blue water scarcity maps to prioritize locations for action. The published report is not clear as to what data and methods were used to locate C&A's supply chain, and it is not performed for a specific product line like blue jeans.

Selection of Case Method: A Hybrid Approach

There are key differences between WFA and LCA in the types of water accounted, the scope of accounting, and spatiotemporal explication of impacts [13]. Given the global nature of Guess?, Inc's operations and limits to data availability, time, and costs for carrying out a study, I agreed with Guess?, Inc. on a hybrid approach. The hybrid approach attempts to leverage the strengths of both the WFA and LCA methods. Table 1 summarizes the key differences between WFA and LCA, and the choices made for the hybrid approach.

For types of water, LCA counts use of surface and groundwater only (blue water in WFA terms), but not rainfall (green water), or water used to dilute pollution (grey water). LCA omits grey water because most polluted water is not treated by dilution in the industrial system, and LCAs account for the energy and chemicals used for the treatment of polluted water or the release of polluted water in other impact indicators (e.g., climate change impacts and human health impacts). Also, in this case study, Guess?, Inc. has a separate set of impact indicators

TABLE 1. Summary for selection of case method

Dimension	LCA	WFA	Hybrid approach
Scope of indicators	Multiple indicators of impact (e.g., global warming, ecosystem health, and human health)	Focused only on freshwater consumption	Water withdrawals and hot spots analysis
Types of water	Blue water only (surface and groundwater *withdrawals*)	Blue water, green water, and grey water	Blue water withdrawals and green water for crops that are sometimes irrigated
Scope of the life cycle	All significant processes from "cradle to grave"	Most studies are "cradle to consumer"	All significant processes from "cradle to grave"
Truncation rules	All constituents, typical cut-off rules are 1–5% or less of impacts or by mass/energy	Only major constituents by mass	Omits only minimal processes or those without water use
Reporting basis	Functional Unit	Total impacts of production	Total lifetime impacts

for wastewater testing and chemical management of its direct suppliers. On these rationales, the hybrid approach ignores grey water.

As for rainfall (green water), the hybrid approach recognizes the importance of accounting for rainfall on crops, because it provides a useful indicator of whether a product system is growing crops in arid areas. Also, as WFN has shown in the development of its datasets, spatial data exist from which to make green water estimates for different types of crops grown in various locations.

The hybrid approach differs slightly from the accounting of blue water in WFA in that it considers not just water consumed at each process step, but rather, as in LCA, the total water withdrawn from the environment. Withdrawals are the total surface or groundwater required for production, including a portion which may eventually be returned. It is often hard to know, as it was in working with Guess?, Inc. suppliers and existing secondary datasets, how much water is returned and where. This makes explicit spatiotemporal accounting infeasible. Therefore, since it is required to withdraw the water for production, measuring total withdrawal as the product demand is the conservative assumption (i.e., the method that reports a larger total water footprint).

The hybrid approach aligns extensively with the WFA method, especially because I use datasets from the WFN data for cotton production and hot spots calculations. However, it also uses LCA datasets, so that it has the sort of completeness to materials and production stages common in LCAs. Table 2 shows that there are few truncations in the hybrid water footprint.

For hot spots analysis, the WFA method seeks to understand the total water burden in given water catchment basins in terms of how much is left for nature after all human uses. In contrast, the WSI measure in LCA seeks to understand the burdens of a single product system across multiple locations *relative* to rainfall totals compared with global averages. Thus, LCA's WSI penalizes product systems that use water inefficiently in water-scarce places but does not indicate whether water resources in given places are fundamentally overwhelmed.

For hot spots analysis, the hybrid approach uses WFA data and methods to calculate the impacts of production on blue water scarcity at various production stages. Also, for the water footprint calculation, the hybrid method does not use a typical LCA functional unit, but instead reports directly the liters of green and blue water required to make one pair of blue jeans and for a consumer to wear it 166 times.

Execution of the Case: Scoping the Spatially Explicit Water Footprint of Blue Jeans

The scope of the study runs from cradle (materials), fabric mills, industrial laundries, and to use (consumer washing). There is no grave because the assumption is that no significant water is consumed in the typical end of life paths for blue jeans (landfilling, incineration, or shredding for insulation). Water withdrawn is summed across this series of carefully delineated and linked processes with both direct use in contract facilities and indirect use (i.e., water embodied in other consumables). Waste, allocations to coproducts, and production efficiency are accounted at each

TABLE 2. Scope of the product system of the blue jeans for the water footprint

Materials	
Inclusions:	**Exclusions:**

• Cotton growing
  ◦ Lint cotton
  ◦ Carded cotton
• Polymer synthetic textile materials
• Manmade cellulosic materials
• Incidental materials (e.g., zipper, labels, etc.)
	• Packaging
	• Tractor fuel
	• Fertilizer production
	• Pesticide production
	• Grid electricity consumption

Fabric mills	
Inclusions:	**Exclusions:**
• Total intake of process water allocated to the production of square meters of fabric	• Dyes • Finishing chemicals
Laundries	
Inclusions:	**Exclusions:**
• Total intake of process water allocated to the production of garments	• Treatment chemicals
Consumer washing	
Inclusions:	**Exclusions:**
• Total intake of water for one load allocated to the mass of one pair of jeans given the average washer's capacity	• Detergent • Fabric softener

step. Major processes that use water are tracked to locations and mapped in GIS using primary data collection and secondary datasets. Municipal water, surface water, groundwater, and collected rainwater are accounted as blue water and occur in all stages of production. Rainfall is accounted as green water and occurs only on crops used for raw materials.

The rules for truncation (at what point to ignore small quantities of indirect water use) are more like typical WFA methods than LCA methods. For example, the study does not consider the small amounts of water consumed in electricity production for the electricity used in each process step. Also, the study does not include water use from transportation, which was mentioned as too small an amount to warrant reporting in the Levi Strauss and Co. 501 blue jeans study where it was measured. Table 2 lists the inclusions and exclusions according to the system boundary.

As shown in Table 2, chemical applications are also excluded from the scope of the analysis due to data availability issues. In the case of cotton production, this truncation is applied in the WFN study for cotton [28]. I used the WFN cotton data [28] to estimate water use for cotton across the Guess?, Inc. supply chain. In the cases of fabric mills and laundries, even though this case study was able to gather primary data on chemicals consumption, no adequate secondary literature on the water used to manufacture the chemicals was available.

Execution of the Case: Locating the Company's Denim and Blue Jeans Production

My first major research step was to describe and locate each of the production steps for blue jeans in Table 2 for Guess?, Inc. To do so, we developed an average profile of materials and locations across the product lines using a sampling approach to provide wider insight about impacts and risks in the total supply chain. First, we characterized the average denim fabric composition across blue jean products lines and the major industrial laundries and fabric mills. Next, with an introduction from the Director of Corporate Sustainability, I interviewed 6 fabric mills and 10 laundries to gather data on their operations. I combined supplier data and trade data to estimate the countries of origin for cotton and locations for textile mills and industrial laundries.

Although we calculated a representative water footprint for a single popular pair of Guess?, Inc. blue jeans, we decided to create an average denim profile for two reasons. First, it is not possible for the company to know which mills produce denim for a given pair of blue jeans. To meet fluctuations in volume and demand, production rotates

TABLE 3. Average denim fabric fiber composition

Fiber type	Composition (%)
Cotton	82
Polymer synthetics	10.5
Wood-based synthetics	7.5
Total	100

among mills. Second, it is important to have insight into the supply chain for more than a single product line.

AVERAGE DENIM FABRIC COMPOSITION. To measure a water footprint, it is necessary to first identify the types of materials used in making denim for Guess?, Inc. While denim can be made with 100% cotton, jeans nowadays are typically made from a blend of materials that include primarily cotton, and also manmade cellulosic materials usually originating from wood (e.g., lyocell, modal) and polymer-based synthetics (e.g., polyester, elastane). These materials are combined with cotton to offer stretch and a lighter weight feel to the garment.

Guess?, Inc. tracked the fabric composition of over 1,000 denim styles purchased during fiscal year (FY) 2017. With input from the production and sustainability teams, I developed a sampling frame for FY 2017, drew a random sample, and manually audited records. Fabric material composition across all denim styles was calculated with an uncertainty of ±6% with 95% confidence. The results in Table 3 show that cotton is the predominant material, followed by polymers and wood-based semi-synthetics.

COUNTRIES OF ORIGIN IN THE SUPPLY CHAIN. Based on the analysis of fabric composition, it is evident that the priority for spatial analysis for raw materials should be the origin of the cotton supply. I estimated the origin of cotton in this study with great difficulty because cotton farms are many steps in the supply chain away from Guess?, Inc. The fabric mills may know the direct supplies of cotton they receive, but the six mills identified as significant in the company's supply chain and interviewed for this case study were generally unwilling to divulge data. Even if they were willing to share detailed data, Guess?, Inc. "nominated" mills for significantly less than half of its orders across all of its brands in 2017. This means that the rest of the mills are selected by and known only to Guess?, Inc.'s direct supplier (e.g., the industrial laundry or the cut and sew operation).

TABLE 4. Estimated country of origin for the cotton supply

Cotton country of origin	Supply (%)
North American Country A	28
Asian Country A	18
Asian Country B	15
North American Country B	11
Asian Country C	11
European Country A	4
European Country B	1
African Country A	1
Others	11
Total	100

To overcome these issues, we first identified the top industrial laundries that directly supply garments to the garment company. Then, I interviewed about 10 of these suppliers and obtained their laundry facility addresses so they could be located on the map. They represented 65% of the total denim supply in FY 2017. Interviews with both the fabric mills and the garment suppliers confirmed that garment suppliers very often order fabric from mills within their own country. Thus, a key assumption was taken that the country of origin for the garment supply was useful as a proxy for the country of origin for the mills.

The 10 industrial laundries in 65% come from four countries. Thus, using global trade data by country from the USDA and the Global Trade Atlas that tracks commodity category, "520100, Cotton, Not Carded or Combed," I developed a table of percentages of likely countries of origin for cotton for mills in those four countries [31, 32]. For the remaining 35% of the supply of unknown origin to the company in the case study, I assumed that the cotton came from the four leading global producers (India, China, the U.S., and Pakistan), according to their percentage rank in global production, and the remaining 29% of this unknown supply was placed in the "other country of origin" category. The output of these calculations is shown in Table 4, where precise identities of countries have been masked for business confidentiality. These figures represent the average global flow of cotton as it has been weighted to represent the supply chain of Guess?, Inc.

Execution of the Case: Calculating the Spatially Explicit Water Footprint

Estimates of water use were developed for each stage of production. For the raw materials, the cotton estimate was made spatially explicit by using the secondary data mentioned above from the WFN for irrigation and rainwater use in cotton production by country [28]. For fabric production and laundries, I developed primary data with the 6 mills and 10 laundries that were interviewed. These data are spatially explicit since they represent the conditions of production in these places. The consumer washing phase is computed to a global average and thus is not spatially explicit.

DATA AND CALCULATIONS FOR RAW MATERIALS. For the cotton in the denim, the figures for green and blue water use for each country in liters of water per gram of cotton given by the WFN data [28] were multiplied against the percentages in Table 4. The other category in Table 4 was multiplied by the unweighted average of all the countries in the data. These figures were then summed to give a weighted average of blue water (4.05 l/g) and green water (4.42 l/g). Finally, an average realization rate from the literature of 86.5% for carded cotton in the fabric was used, because not all seed cotton harvested is suitable for denim production [33].

To complete the calculations of water withdrawal for denim in the Guess?, Inc. supply chain, I combined these figures for cotton with figures from secondary LCA literature for embodied water for the materials sourced from polymers [34] and sourced from forest resources [35]. Specifications for the pair of blue jeans made by the case study company provide fabric area, and I worked out a conversion factor for the area to mass from secondary literature on blue jeans fabric [24]. I estimated that it takes 421.3 g of cotton and 82.3 g of synthetics to make one pair of jeans. Water use for incidental materials (e.g., buttons) was similarly calculated from secondary literature, but the masses of the incidentals were so small relative to the denim fabric that the calculations were performed mostly for the sake of completeness.

DATA AND CALCULATIONS FOR FABRIC MILLS. I worked with the six mills to develop an estimate of each mill's water use per square meter of denim fabric. Estimates were not precisely instrumented but rather based on reported intake water values divided by the total production of square meters of fabric for reporting periods, ranging from 1 month to 1 year's production. Reported values had an unweighted mean of 28.2 l/m^2 with a standard deviation of 12.0 l/m^2. The unweighted average was used in the footprint calculation.

DATA AND CALCULATIONS FOR THE INDUSTRIAL LAUNDRIES. The process of cutting, sewing, and laundering fabric only uses water directly in the laundry step when the garments are washed to achieve wear and the desired coloring patina. I worked with the 10 industrial laundries to develop an estimate of the liters of wash water per kilogram of garments washed. Again, estimates were not precisely instrumented but rather based on reported intake water values divided by total production. The industrial laundries measure production volume by piece washed, so I worked with them to develop a conversion factor of an average of 0.6 kg/garment. Despite the low precision, reported values were in a reasonable range with a mean of 0.6 kg/garment and a standard deviation of 0.06 kg/garment. In this case, the production volumes in the company's supply chain can be estimated, so I calculated a weighted average of 106 l/kg.

DATA AND CALCULATIONS FOR CONSUMER WASH. Since Guess?, Inc. blue jeans are sold and worn all across the world, it is impossible to make spatially explicit measures of consumer wash water. Still, attention to water, energy, and chemicals in the consumer wash phase has been a key feature of previous studies of blue jeans, so I included an estimate for this in the footprint. Previous data on wears and wears per wash were used to estimate washes for 166 wears in a lifetime [23, 26]. Data on washing machine efficiency for the U.S., Western Europe, and China were taken as an unweighted averaged to develop a value for wash water per kilogram of home laundering [36]. Using the mass for the pair of blue jeans in this study, I calculated the blue water used in washing. These three regions were chosen to represent major consumer markets, but I did not have data on country-by-country sales for Guess?, Inc. products or washing machine performance with which to refine this estimate for possible spatial variation.

SPATIALLY EXPLICIT WATER FOOTPRINT RESULTS. The results in Table 5 are largely consistent with previous LCA's, though some differences are worth highlighting. Consistent across studies is that raw materials (64%) and the consumer wash phase (32%) dominate the blue water footprint. The fabric mills (2%) and the industrial laundries (2%) play a much smaller role. The study for Levi Strauss and Co. that is not spatially explicit shows slightly more water for fabric mills

TABLE 5. Spatially explicit water footprint results (one pair of blue jeans)

Stage of production	Water use total (l)	Total (%) (blue water)
Raw materials	1,729 l of blue water 2,031 l of green water	64
Fabric mill	44 l of blue water	2
Industrial laundry	48 l of blue water	2
Consumer wash	880 l of blue water	32
Total	**2,701 l blue water** **2,031 l green water**	**100**

and less for industrial laundries than for this study [23]. Perhaps this is due to adjustments made for Guess?, Inc.'s supply chain to make the results spatially explicit.

Another key result from the water footprint is that out of the raw materials, cotton dominates the blue water used, constituting 98% (the polymers and wood-based fibers contribute almost nothing despite being 18% by mass). This is in spite of the fact that the company in this case study draws its cotton supply from countries that use slightly more green water than blue water relative to global averages. A company that sourced differently could have an even higher blue water footprint.

Mapping Water Impact Hot Spots

In LCA, the term "hot spot" often refers to identifying stages of production that make outsized relative contributions to impacts. In this case study, it has this meaning but then extends to identifying the locations (places) where the worst impacts are realized. It is worth noting that it is not at all the same as the group of spatial statistics used to detect point clustering often referred to as "hot spots" (e.g., crime heat maps). Given the results just described, it is evident that analyzing spatial impacts for cotton production is key, and the analysis here focuses exclusively on this for raw materials production. However, since Guess?, Inc. influences industrial laundries, and to lesser extent fabric mills, a hot spots analysis was also applied to these stages of production.

THE HOT SPOTS METHOD. According to the WFA method, a hot spot in a water footprint of a product highlights catchment basins (watersheds) where there is a lack of available blue water relative to existing ecological and human needs in that area, and the product system uses a large amount of blue water [27]. The WFA method gives the following formula:

$$WS_{blue}[x,\, t] = \frac{\sum WF_{blue}[x,\, t]}{R_{nat}[x,\, t] - EFR[x,\, t]}$$

In this equation, blue water scarcity (WS_{blue}) is defined as the size of the human blue water footprint in a catchment x at time t divided by the blue water produced by nature (R_{nat}) less the environmental flow requirement (EFR) in catchment x at time t. What this means is that a blue water scarcity value of 1 or 100% represents blue water fully consumed within ecological limits, but a blue water value higher than this is not sustainable. Lower values are preferred, and they are dimensionless values that facilitate comparisons of water stress created by supply chains at various geographical scales.

The WFN provides data to help with this calculation that gives blue water scarcity in a raster GIS file with 30 × 30-arc minute grids [37]. These grids provide estimates at monthly time scales and as annualized averages. The annualized averages were used because in the case of cotton production the timing of irrigation is not known, and it was assumed that mills and industrial laundries produce consistently throughout the year. To identify hot spots, I overlaid the water use measured in this study for known locations on the map of blue water scarcity values and then multiplied the water use value in the supply chain against these blue water scarcity values.

For cotton production, I calculated hot spots at the scale of countries. This was the only way the data on water use could be geocoded, but the varying size of countries is a concern. First, the raster data on blue water scarcity were clipped to each country's boundaries and averaged. Next, the amount of blue water used from each country to produce a kilogram of cotton in the company's supply chain was estimated using the global supply weighting approach described earlier. These two figures were then multiplied. To summarize, countries that supply relatively more cotton to this supply chain, countries with relatively high amounts of blue water use in cotton production, and countries with the highest blue water scarcity measures take on the highest values.

Fabric mill locations were geocoded as a point from addresses. Thus, the analysis used the blue water scarcity value of the 30 × 30-arc minute grids where the point representing the mill was located (i.e., no need to average by country). The study used the estimates developed during interviews of blue water intake normalized to

TABLE 6. Hot spots analysis for cotton supply

Country	Blue water amount in the supply chain (m^3/metric ton)	Blue water scarcity value (dimensionless)	Water impact metric (dimensionless)
Asian Country A	1,600	4.69	7,507
Asian Country C	530	3.73	1,977
North American Country B	431	4.49	1,936
North American Country A	375	1.49	558
European Country A	280	1.10	309
Asian Country B	257	1.85	476
European Country B	43	1.31	57
African Country A	38	5.34	203
Other	491	n/a	n/a

production volumes for each mill in liters per square meter. There was no weighting of the mills since production volumes are about even in the supply chain. To summarize, mills with the most water used per square meter at a given facility in the most water-scarce areas take on the highest values (i.e., unweighted for the supply chain.)

For determining hot spots for the industrial laundries, water use at each in liters per kilogram was multiplied against blue water scarcity values. As with the fabric mills, I used the precise data, associating a geocoded point for each industrial laundry with the raster map for blue water scarcity. Unlike in the product water footprint, the factory laundries are not weighted by their influence in the Guess?, Inc. supply chain for the spatial analysis. To summarize, industrial laundries with the most water used per kilogram washed in watersheds with the highest level of blue water scarcity take on the highest values.

RESULTS FOR WATER IMPACT HOT SPOTS. For the countries producing cotton, there are notable differences in both average blue water scarcity values (ranging from 1.10 to 5.34) and the amount of blue water estimated to be used in cotton produced for this company's supply chain (ranging from 38 to 1,600 m^3/metric ton). Table 6 orders the countries in the supply chain from highest to lowest water impacts. As in Table 4, precise identities of the countries have been masked for reasons of business confidentiality. Three countries, Asian Country A, Asian Country C, and North American Country B, stand out as having much higher water impact metrics and can properly be identified as hot spots. Of note, Asian Country C was ranked fifth in percentage of supply but rose to the second rank for water impacts.

For the fabric mills, there are notable differences in blue water scarcity values at their facility locations, ranging from 0.216 to 6.75. Also, recall that the mean water use at the fabric mills is 28 l/m^2 with a standard deviation of 12. Despite this fairly wide variation in the primary mill operations data, the blue water scarcity variation is higher: the second most water-efficient mill out of the six becomes the second-highest mill for water impacts because it has the highest blue water scarcity. Two out of the six facilities stand out as significantly higher in water impacts.

For the industrial laundries, the blue water scarcity values at the facility locations have a huge range from 0.00288 to 6.36. The primary data on water use at the laundries also have a large range, with a mean of 137 and a standard deviation of 97.0 l/kg. Despite this wide variation, there is so much variation in the blue water scarcity values that, with but one exception, the industrial laundries are effectively ranked by the blue water scarcity value alone for overall water impact.

CONCLUSION

Reducing the water footprint of denim products is a challenge not just only for Guess?, Inc. but also for the entire apparel sector. Spatial variation in water scarcity matters significantly in how water impacts are felt in the apparel supply chain. Improving the supply of cotton, which includes increasing irrigation efficiency and yields while reducing production in water-scarce areas, is the major issue. However, as points of action are determined, the limitations of the analysis must also be kept in mind.

Limitations and Future Work

Although this study was built carefully from the best data that could be obtained, most data in this study are of low to moderate precision and so the results should be treated as having large margins of uncertainty. As disclosed above, I developed the data on country of origin based on suppliers that represent only 65% of the company's overall supply chain and an uncertain link of these suppliers to mills and in turn cotton. As with most companies in the apparel sector, it is very hard to know which mills actually produced what textiles and where the substrates were sourced.

The data on how cotton uses green and blue water were published by the WFN in 2005. One important limitation of these data is that the climate data from 2005 and earlier may or may not represent the irrigation needs of cotton. Green water is a measure of the amount of evapotranspiration and uptake in the cotton of infiltrated rainwater in the growing of the cotton. When not enough green water is available, blue water (surface and groundwater) must be substituted via irrigation. Additional irrigation water might be needed in particular regions due to climate change if they were either hotter (leading to more evapotranspiration) or drier (providing less green water). To help the company to understand future risks in its supply chain, these cotton irrigation models should be updated by combining with climate models.

One key limitation in the country level-analysis for cotton hot spots is using the country boundaries itself as the spatial unit. This is known in spatial sciences as a modifiable areal unit problem (MAUP). This may be especially problematic in countries with larger land masses that have a significant variation in blue water scarcity from one region of the country to another. It is possible that cotton growing in such countries is mostly or exclusively done in either blue water-scarce or blue water plentiful areas. In the future, if updated and reliable spatial data sets for cotton-growing regions in each country in the supply chain could be developed, for example with remote sensing, the precision here could be improved. Even if we did not know exactly which fields provided cotton a given company, the country-level figures would be more precise.

Actionable Results for Companies

To reduce the water footprint may require taking greater control of the cotton supply chain itself. The task of asserting greater control over all parts of the supply chain is a long-sought goal in the apparel industry, and some efforts have been made to develop sector-wide social responsibility data for garment suppliers [38]. Companies have started to use such data to exercise control of direct garment suppliers, but it is much more challenging to do this for cotton supplies given the way supply chains are currently structured.

One hopeful sign in the global cotton supply is the nascent development of a sustainable commodity procurement framework called the Better Cotton Initiative (BCI). The BCI approach is to work with apparel industry partners to transfer knowledge, for example on improved irrigation practices, to cotton farmers across the world [39]. They do not directly trace cotton to the source in any given company's purchases, but they allow companies to purchase credits that stimulate the market for cotton grown in their program, and in return companies can identify their cotton as BCI-sourced.

One approach that companies in the apparel sector could take would be to support BCI efforts on technologies and knowledge transfer to increase yields and reduce irrigation in countries that are known water hot spots in their particular cotton supply. They could also arrange for the expenditure of BCI purchasing credits on farms that they suspect contribute to their supply chain in such locations.

The BCI approach, however, faces real limits in that even if yields become much higher and irrigation is greatly reduced, the most arid locations with high current water demands may still be overshooting freshwater resources, with social, political, and ecological consequences. Ultimately, raising the bar for particular companies, or as the BCI aims across the entire industry, may require the development of "do-not source" lists that are enforced from mills down through suppliers. In any case, having the technical ability to analyze overshoot in different parts of the supply chain across various locations is a prerequisite for either targeting technological improvements or, with caveats regarding precision, re-directing global sourcing in effective ways [22].

To reduce the water footprint of the blue jeans products, it might also be possible to focus on the consumer wash phase. Levi Strauss and Co. is famous for its "wash less and line dry" campaign [40]. The 501 blue jeans LCA's results are explained to consumers and the company seeks to convince them to reduce the number of washes and that electric drying is harmful to the look, feel, and durability of the jeans.

Another strategy might be to experiment with denim styles that increase the use of synthetic and manmade cellulosic materials rather than cotton. While this might reduce the water footprint, one might reasonably hypothesize that it would raise the carbon footprint or total nonrenewable energy use. It is very important to keep a balanced set of environmental indicators in mind (e.g., human health and climate change), even as detailed work on the water footprint is carried out. Impacts from sourcing in forests for manmade cellulosic materials and the use of non-renewable energy in polymer-based synthetics would need to be measured and minimized.

Taking effective action is inherently difficult in the post-Fordist political economy. In post-Fordist production, firms that design and sell consumer products manage far-flung supply chains in return for increased bargaining power over labor to drive down costs and to meet rapidly changing demands in the consumer market. A few firms may take greater control of one or another aspect of the supply chain for claims of social responsibility, but to manage the entirety of supply chains for corporate social responsibility is nearly contradictory with economic imperatives that confront individual firms. Action will need to come from across sectors, non-governmental organizations, and governments to create sustainable global water footprints across the consumer products industry.

CASE STUDY QUESTIONS

1. What recommendations could you make to the company or the apparel industry based on these results? List one or two key recommendations. Argue for their feasibility and identify additional information needed to execute them.

2. Consider the methods and data described in the article. What limitations should you acknowledge when sharing these results with decisionmakers? Is there anything in this study that is not spatially explicit that would affect the results if the parameter could be differentiated by location (e.g., realization rate of cotton)? List and describe at least 2–3 key limitations.

3. Would you recommend that the company change its sourcing based on your analysis? If so, how? What else would you want to know before giving such a recommendation?

4. What sorts of spatial data and models would be needed to consider the problems of economic or political scarcity of water resources? Do some research to see if these exist.

5. Consider the MAUP as it is described related to averaging blue water scarcity values by country in this article. Using a GIS software of your choice, download the blue water scarcity values from the WFN for the four leading cotton-producing countries in the world [41]. Make a map of these data and then look to see how blue water scarcity is distributed in these countries. Next, try to find digital maps or qualitative descriptions of where cotton farming is located in these countries. What does this tell you about how the MAUP may have affected the results in this study?

6. Using GIS software of your choice, locate and download a model of changes in rainfall patterns due to climate change. How does this model align with the WFN data on blue water scarcity? How does it affect the four leading countries for cotton production?

7. Look up the marketing materials for the Levi Strauss and Co. campaign on wash less and line dry. Do you think this sort of campaign to change consumer care behavior is this useful? Why/why not? Can you find any data to suggest that consumer behavior has changed or is changing?

AUTHOR CONTRIBUTIONS

RV gathered the primary and secondary data, developed the water footprint model, led the hot spots analysis, and wrote the case study presented here.

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COMPETING INTERESTS

The author has declared that no competing interest exists. Although Guess?, Inc. reviewed and approved publication of the case study with regards to disclosures of business information, the opinions expressed here are entirely the author's views. Guess?, Inc. neither funded the development of the case study article nor endorses its views.

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