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RESPONSE FUNCTIONS IN THE CRITICAL COMPARISON OF CONJUNCTIVE MANAGEMENT SYSTEMS IN TWO WESTERN STATES

by

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1.1 INTRODUCTION

Conjunctive management of surface and ground-water resources on state and local levels is a relatively new political phenomenon. This type of management has evolved, in part, in response to growing populations with ever-increasing, and often conflicting, water demands. In addition, a more sophisticated technical understanding of the physical link between groundwater and surface waters has led water managers to reconsider historical strategies for solving water supply problems. In light of growing demand and improved technology, some western states have begun the transition from crisis-oriented water management to one of long-term planning for population growth and environmental protection. This planning process requires that the constituents of a region define their water use goals and objectives so that various approaches to conjunctive management may be evaluated for their suitability to that particular physical and socio-political environment.

1.2 HISTORICAL BACKGROUND

Before examining some of the conjunctive management schemes adopted by modern water managers, one should explore the circumstances out of which the current practices evolved. Not too surprisingly, the geographical setting of the arid west and its place in American history played very important roles in determining the fate of western water management.

Historically, American water law evolved from the British law of riparianism into the more flexible "reasonable use" doctrine. While the American rule of riparianism still embraced the belief that groundwater and surface waters were two entirely separate and distinct entities, it did permit water uses that somewhat diminished the streamflow as long as the uses were "not unreasonable in relation to the other uses made of the watercourse by co-riparians."[1] By the mid-1800's, miners and agriculturalists who settled in this country were faced with several problems relating to the riparian doctrine: 1) they did not own land (a requisite for using surface water under the riparian doctrine), 2) no provision yet existed for individuals to purchase land from the United States government, and 3) miners and farmers often needed water in places far from streams and rivers. Consequently, pioneers simply used public lands for their activities and brought water to where they needed it.[2] These types of issues gave rise to federal mining laws enacted in 1866, 1870, and 1872, which permitted the staking of private claims on public lands and acknowledged and upheld those water rights which "had already been accrued and were recognized by local law or custom..."[3] The Desert Land Act of 1877, perhaps invadvertantly, strongly influenced the direction of western water law with a clause in its provision for the disposition of land that stated:

> "...all surplus water over and above such actual appropriation and use...upon the public lands and not navigable, shall remain and be held free for the appropriation and use of the public for irrigation, mining and manufacturing."[4]

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1 Sax, J. L. and R. H. Abrams, Legal Control of Water Resources; cases and material, West Publishing Co., 1986, p. 156.

2 Ibid, pp. 293-4.

3 Ibid, p. 298.

4 Ibid.

After 1877, a tortuous course of precedent-setting legal battles, including most notably *Coffin v. Left Hand Ditch Company*, *Lux v. Haggin*, and *California Oregon Power Co. v. Beaver Portland Cement Co.*, determined the nature of the states' and the Federal Government's roles in defining water law. With Coffin v. Left Hand Ditch Company, Colorado (ruling that riparian rights never applied in that state) rejected riparianism entirely and adopted a system of pure prior appropriation. California used Lux v. Haggin to declare that federal land grants brought with them riparian water rights unless they were expressly withheld, and that California water law would recognize riparian rights as superior to all appropriation rights, but the system would be one of dual water rights. The case of the California Oregon Power Co. v. Beaver Portland Cement Co. finally convinced the Supreme Court that Congress did not grant riparian rights to patentees of federal land, and served to reiterate the Court's position that "Congress cannot enforce either rule upon any state."[5]

Traditionally, all jurisdictions in the United States administered groundwater under the rules of common law. The "English Rule," or rule of absolute ownership, specified that the owner of land overlying an aquifer had absolute right to extract the water below his property. In adopting this rule, the courts dismissed the possibility of a connection between groundwater under one person's land with that under his neighbor's since the precise path of the groundwater was unknown (see *Roath v. Driscoll*, 1850).[6]

With time, the legal disregard for harm done by one groundwater user to another lost favor, and most states replaced the English Rule with the so-called "American" or "reasonable use" rule. This modification to the more stringent English Rule simply constrains a landowner to the use of groundwater from beneath his land in a manner

[5]Ibid, pp. 298-317.

[6]Ibid, p. 787.

which is "reasonable and beneficial" (on his land) and which is not injurious to others. The American rule remains restrictive, however, and some states have looked to the second Restatement of Torts Section 858 (1979) for more flexibility to handle different situations involving injury to other users of the common pool resource. The Restatement of Torts allows consideration of the nature and extent of harm done instead of forcing a decision based strictly on the fact of injury. Furthermore, the Restatement of Torts does not contain the American rule's requirement that the groundwater be used on the overlying tract of land.[7]

The legal recognition of a physical connection between surface and ground waters extends back to the late 1920's, but the active active management of groundwater and surface waters as inseparable and highly interdependent resources came to most of the western United States much later.[8] In contrast to the speed with which scientific understanding of the physical interrelatedness of groundwater and surface waters has evolved, the separate and conflicting legal systems governing the two natural resources have been slow to converge.

Today, California, Colorado and New Mexico are notable among the western states for their working conjunctive management systems. The development of high-lift pumps in the 1930's helped to focus attention on groundwater and led to some of the first legislation on the issue. California's Water Conservation Act of 1929 initiated the regulation of groundwater resources in California in the 1930's, when salt water intrusion and land subsidence first appeared (near San Jose) as the result of excessive groundwater pumping.[9] New Mexico first experienced groundwater regulation about

[7]Ibid, p. 792.

[8]Clark, Ira G., Water in New Mexico, A History of Its Management and Use, University of New Mexico Press, 1987, pp.233-242.

the same time, but the emphasis there was on artesian aquifers because of their obvious and relatively sudden reaction to pumping.[10] Colorado lacked any regulation specific to groundwater until the 1950's, and only since the late 1960's has the state begun to study the interdependence of groundwater and surface water in its attempt to develop a rational basis for the development and integrated use of groundwater.[11]

1.3 FOCUS OF STUDY

In spite of some impressive tenures, these conjunctive management structures continue to evolve as their managers learn more about the complexities of each area's problems and needs and about the mechanisms governing the physical systems at hand. For the purposes of this study, three conjunctive management schemes from two western states were selected for comparison.

From California, the Santa Clara Valley Water District and the Orange County Water District exhibit similar administrative allocation systems with slightly different methods and objectives. These districts operate under the umbrella of California's *correlative rights doctrine*, which emphasizes a proportional sharing of water shortages among users. In addition, the Santa Clara Valley basin has not been adjudicated, and thus, individual groundwater rights do not exist. Instead, the management district assumes responsibility for administering all water resources to best serve the needs of the community. While much of the Orange County basin has been adjudicated, the management District still manages combined surface and groundwater resources of the

[9]McArthur, Seonaid et al., eds., 1981, "Water in the Santa Clara Valley: a History," Local History Studies: California History Center, De Anza College, vol. 27.

[10]Clark, 1987, p.241.

[11]Daubert, J., 1978, Conjunctive Ground and Surface Water Allocations: the Economics of a Quasi-market Solution, Master's Thesis, Economics Department, Colorado State University, p.14.

area.

From Colorado, the Groundwater Appropriators of the South Platte (GASP) system of conjunctive management provides contrast to the California systems described above. Conjunctive management practices in the South Platte area of eastern Colorado arose primarily from the need to serve agricultural interests while adhering to the legal constraints of the *prior appropriation doctrine.*

1.4 PURPOSE

The purpose of this paper is two-fold: to compare different types of conjunctive management systems, and to illustrate the use of response functions in a practical application. While the computer models described in this paper were designed to include the most general and characteristic features of real, functioning systems, the reader should realize that the models represent great simplifications to the "real world". Each model attempts to simulate only the *general managerial character* of each system type for the purpose of comparison, and is not an accurate representation of any real system.

1.5 PROBLEM STATEMENT

The interconnectedness of groundwater and surface waters in some areas leads to natural interference between neighboring users of those resources. This interference, either in the form of decreased streamflows because of pumping-induced river leakance, or decreased recharge to the aquifer as a result of diverted streamflows, is complicated by a lag in time between the action and the resulting effect. For example, the depletion of streamflows due to ground-water pumping at a location distant from the river may not be felt in the stream for several years, depending on the well's proximity to the stream and the hydrologic properties of the aquifer system. The problem is compounded by the superposition of many such effects in space and in time as the number of users increases. These complexities, combined with changing local and regional priorities (political and environmental), pre-existing water rights, and historical water laws make conjunctive management a dubious task for even the smallest communities.

By incorporating the relevant hydrologic information and the management rules for a given system, the computer models designed for this study allow us to examine the sensitivity of each management system to permutations in combined hydrologic settings and user demands. During the simulations, the models preserve the link between the hydrologic environment's ability to satisfy user demands and the effect of users' actions on the hydrologic environment.

1.6 CONTRIBUTION OF THE REPORT

This report presents two flexible computer simulation programs by which a user can experiment with alternative rule sets for the conjunctive management systems described under different economic and physical conditions. The use of linear response functions in a linked management/hydrological model for a multi-aquifer system and under conditions of non-linear capture from internal boundary sources provides a good example of the power and flexibility of the response function method.

Chapter 2
Water Law and Management Systems

2.1 PRIOR APPROPRIATION SYSTEM

Many western states administer surface water rights according to the prior appropriation doctrine, often referred to as "*first in time, first in right.*" Under this doctrine, those who appropriate surface water from a stream or river are ranked by seniority in the order of their appropriations in time. Thus, the first person to divert water from a river and put it to a "beneficial use," thereby claiming his water right, has a right of higher priority than of any others who follow. Any shortage in streamflows required to meet existing rights results in diminished or discontinued diversions to the most junior right holder first, then the next junior, and so on until the needs of the most senior rights holders have been satisfied. Non-use or non-beneficial use of diverted water results in forfeiture of the water right.

The conjunctive management system which incorporates the Groundwater Appropriators of the South Platte organization (GASP) in Colorado provides an ideal example of a management system operating under the prior appropriation doctrine. The following paragraphs provide an overview of the evolution of groundwater regulation and administration in the South Platte Basin of Colorado.

2.1.1 Groundwater Appropriators of the South Platte (GASP), Colorado

Colorado's formal adoption of the prior appropriation system was initiated with the federal case *Broder v. Natoma Water & Mining Company* in 1979, and finalized with the Colorado Supreme Court's 1882 decision in *Coffin et al. v. Left*

Hand Ditch Co. Broder v. Natoma marked the federal government's first clarification regarding its position on water rights acquired by appropriation before the mining Act of 1866 declared public mineral lands free and open to mineral exploration. With this case, the U.S. Supreme Court proposed that the 1866 Act did nothing to diminish the rights claimed before that date, but rather it was a "voluntary recognition of a pre-existing right of possession."[12]

In the landmark Coffin case, the state heard arguments from owners of land adjacent to St. Vrain Creek claiming that they had a "better right to the water" because their lands lay along the creek. The appellee, J. Helm of the Left Hand Ditch Co., argued that, although he diverted water from St. Vrain Creek to another water shed for irrigation purposes, his water right was superior to those claimed by the appellants because his diversion was initiated before they claimed any right to the water in St. Vrain Creek. The Colorado Supreme Court sided in favor of the Left Hand Ditch Co., reasoning that "imperative necessity" of water for artificial irrigation in the arid region of Colorado superseded the application of the riparian doctrine in that area.[13]

By the turn of the century, reliable surface flows in many Colorado rivers, including the South Platte, had already been fully appropriated. Prior to the 1950's (about when energy-efficient ground-water pumps became widely available), Colorado made no effort to regulate ground-water development. Even though the Colorado courts had maintained since 1893 that groundwater "tributary" to surface flows is governed by the prior appropriation doctrine, most wells remained unadjudicated.[14]

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[12]Sax and Abrams, pp. 304-305.

[13]Ibid, pp. 300-305.

[14]MacDonnell, L. J., 1988, Colorado's Law of "Underground Water": A Look at the South Platte Basin and Beyond, *University of Colorado Law Review*, vol. 59, pp. 586-587.

In 1957, Colorado passed a law requiring permits for new wells to be obtained from the state engineer. This law provided for retroactive appropriations dating back to the true date of initiation, thereby preventing any downgrading in seniority that might have resulted from a failure to adjudicate one's right at the time of the groundwater appropriation. In 1965, the state engineer took the position that he "had no authority to regulate well pumping in order to protect surface rights." In response to the state engineer's claim, the legislature passed the Groundwater Management Act of 1965 directing the state engineer to administer both surface waters and "underground water tributary thereto" according to the prior appropriation doctrine.[15] After the state engineer, operating without any firm guidelines, shut down 39 wells in the Arkansas River Valley to protect senior surface water diverters, the Colorado Supreme Court ruled on the important case known as *Fellhauer v. People.* The Colorado Supreme Court used this ruling to uphold the state engineer's fundamental authority to regulate pumping wells to protect vested senior rights, but also to clarify the appropriate conditions for such regulation. The court stated that: 1) the regulation must be done "pursuant to a plan which is implemented through rules and regulations"; 2) the regulation must result in a "reasonable lessening of material injury to senior rights"; and 3) the state engineer should attempt to place conditions on well operation "in a manner that would permit continued use of groundwater without material injury to senior users." The court further encouraged the use of groundwater by stating that "there shall be *maximum utilization of the water of this state*" and by referring to that doctrine's integration "into the law of *vested rights.*"[16] These guidelines and the "doctrine of futile call", which prohibits senior appropriators from taking more water

[15]Ground Water Law of 1957, 1957 Colo. Sess. Laws, ch. 289, § 5 (codified at Colo. Rev. Stat. § 148-18-2 (1963)).

[16]MacDonnell, pp. 586-587.

than they can immediately put to beneficial use, redefined the policy for applying the appropriation doctrine to groundwater.[17] The new policies permitted the use of groundwater by junior appropriators as long as no material injury resulted to senior rights holders, and limited the water taken by senior appropriators to that which they could put to beneficial use.[18]

In 1969, the Water Rights Determination and Administration Act incorporated the principles outlined in the Fellhauer case, thereby requiring the state engineer to consider the interrelationships between ground and surface waters and to maximize beneficial use in his administration of all state waters. The state engineer used stream depletion factors,[19] which indicate the effects of pumping from different locations on surface flows, to integrate water use. The use of this technique for groundwater and surface water integration acknowledged the time lag between pumping and stream depletion. Thus, since 1969 Act provided for the curtailment of pumping only when direct injury to senior surface rights would be avoided, the state engineer could take advantage of the time lag to permit continued pumping until surface rights were actually threatened.[20]

The 1969 Act included three other important facets. First, the Act further encouraged well owners to adjudicate their rights by providing a three-year grace period under which previously undecreed rights would be adjudicated according to their

[17]Daubert, J., p. 55.

[18]MacDonnell, p. 587.

[19]A stream depletion factor incorporates the aquifer transmissivity and specific yield plus the distance from the well to the stream into one parameter. This parameter is then used to calculate the time from the beginning of steady pumping until 28% of the volume pumped derives from stream depletion. Thus, a 100 day sdf means that after 100 days of pumping, the well would have depleted the streamflow by 28% of the total water pumped (see MacDonnell, p. 581).

[20]MacDonnell, p. 588-589.

The 1969 Act included three other important facets. First, the Act further encouraged well owners to adjudicate their rights by providing a three-year grace period under which previously undecreed rights would be adjudicated according to their original appropriation date. Second, because many well owners also had more senior surface water rights, the state engineer was given wide discretion in permitting the use of wells as alternate points of diversion for those surface water rights. Third, the 1969 Act called for a "*plan of augmentation*" for groundwater pumpers. This program, along with a companion bill authorizing water users to provide a substitute water supply to senior right holders, provided a more flexible means for using water outside the strict priority system. Essentially, as long as the water court approved of the plan, groundwater users could pump as much water as they could put to beneficial use as long as they compensated senior water rights for any damage they suffered as a result of the pumping. Under the substitute water supply bill, as long as the water is of comparable quality and continuity to meet the requirements of the normal use of the senior appropriation, the senior rights holder must accept the substituted water supply.[21]

In keeping with the movement to maximize and integrate water use in the state, a group of well owners in the South Platte Valley organized the Groundwater Appropriators of the South Platte (GASP) in 1972. This non-profit group coordinated to mitigate any damages to senior rights caused by pumping from its members' wells in order to avoid curtailment of pumping at its wells by the state engineer. GASP proposed to provide replacement water to the state engineer for use at his discretion. To help determine the appropriate quantity of replacement water in advance, the group offered to provide the state engineer with a list of its members, estimates of the volume of water its members would be pumping in the upcoming season, and an account of the

[21]MacDonnell, p. 589.

actual amount of water withdrawn in the preceding year. The state engineer welcomed the efforts of the group, but expressed his concern that GASP be able to supply enough water to prevent injury to senior rights in the event of a "call" on the river.[22]

As of 1988, GASP had roughly 1400 members operating more than 3000 wells in the South Platte, primarily south (downstream) of Greeley, Colorado. Most of the wells supply irrigation water, with a few also supplying water for municipal and industrial uses. In order to purchase the replacement water needed to offset injuries to senior rights, GASP charges each member an annual fee based on the quantity of water he expects to pump in the upcoming year. One unit of membership must be purchased for each 100 acre-feet (or fraction thereof) of water pumped. New members must pay an initial fee equivalent to what would have been the sum of all of the annual charges since 1972. After the first year, members pay only unit fees each year. The annual unit fee is set by the board of directors, and has risen from $15 in 1972 to $90 in 1986.[23]

While GASP promised to provide information to the state engineer regarding the volumetric pumping by its members, the promised information has only recently been delivered, and no clear policy for defining the required amount of replacement water has ever been spelled out. Originally, the 1974 Amended Rules and Regulations for the South Platte issued by the state engineer set the replacement water supply requirement at 5% of the projected annual volume of groundwater pumped. If the 5% replacement was found to be insufficient, the actual depletion caused by each well's pumping would be calculated using an approved method.[24] In practice, however, GASP never used the

[22]Ibid, pp. 590-591.

[23]Ibid, pp. 591-592

[24]Ibid. The Rules mention the Glover method. Approval is required by the state engineer.

"5% rule" as a basis for determining its replacement water supply. Instead, GASP operates under a "call management" plan. Instead of attempting to calculate the amount GASP wells' pumping would injure surface rights, GASP simply tries to provide enough replacement water to satisfy senior appropriators. GASP strategically locates replacement water supply wells to satisfy valid senior calls on the river in times when historical surface flows would have been adequate. More than half of the replacement water comes from other groundwater wells.[25] This feature of GASP's system exploits the time lag between the initiation of pumping and the time of depletion due to that pumping. By using wells to replenish supplies depleted by other wells, GASP risks a complicated situation of displaced depletion. Practically, though, the replacement water supply wells provide an immediate solution to the problem, and any ill effects of pumping in these wells seems to have drawn little attention. By staving off the problem at the senior diversion points, GASP protects junior rights holders who would normally be forced to forfeit water until the senior calls were met.

In addition to pumped groundwater, GASP provides replacement water from reservoir storage, direct flow rights, and through recharge projects. GASP purchases "recharge credits" for water accumulated by recharge projects operated by other agencies or groups. While reservoir storage is a highly dependable source of replacement water, its capacity is limited. Groundwater storage is particularly attractive because it makes use of otherwise undiverted water during low-demand times and because of its virtually limitless capacity.[26]

[25]Ibid, p. 593.

[26]Ibid, p. 595.

2.1.1 Fort Morgan

GASP is only one of several groundwater users organizations involved in conjunctive management in the South Platte Valley. The Fort Morgan Reservoir and Irrigation Company (hereafter referred to as Fort Morgan) operates under under a well-defined plan of augmentation. In contrast to GASP, Fort Morgan uses its plan of augmentation to protect its pumping operations permanently by incorporating them directly into the state priority system. Fort Morgan owns a fairly senior direct flow right as well as the majority of shares in the Jackson Lake Reservoir Company which operates Jackson Lake Reservoir. Although Fort Morgan members use wells for part of their irrigation water supply, these wells have such junior rights that they would ordinarily be prohibited from operation. Under a court-approved (as of 1985) plan of augmentation, however, the Fort Morgan wells are allowed to operate. The augmentation plan requires the calculation of stream depletions resulting from pumping in Fort Morgan wells, and some scheme for replacing those depletions. Fort Morgan uses an elaborate accounting system for deducing the amount of groundwater used in irrigating its own crops. This value is then converted to a corresponding pumping rate for each well, and then stream depletion factor for each well is used to calculate both the amount and the timing of stream flow lost to each well.[27]

Instead of addressing individual calls on the river, Fort Morgan operates its augmentation plan primarily through a recharge program. Fort Morgan diverts water out of priority from the South Platte River and transfers it to various recharge locations. The amount of recharge is calculated as the difference between surface inflows and evaporation losses plus any flows leaving the recharge site. For a successful

[27] Ibid, p. 597.

augmentation plan, accretions in the stream from recharge must equal or exceed any depletions due to pumping at any time when a senior right would suffer from the loss of that stream water. In the event that recharge fails to meet the replacement water supply needs of senior appropriators, Fort Morgan must supply additional water from Jackson Lake Reservoir or by forfeiting all or some of its direct flow right.[28]

Fort Morgan differs from GASP in its fundamental approach to providing replacement water. GASP operates on the basis of satisfying any calls on the river, while Fort Morgan attempts to prevent such calls by carrying out a precise recharge program designed to meet the expected needs of senior appropriators.

2.13 New Mexico

Groundwater exploitation began near the turn of the century in New Mexico. Abundant artesian water drew prospective farmers to the state as early as the 1850's, but technological problems, specifically the high cost of energy associated with pumping, inhibited the full-scale exploitation of groundwater for nearly a century. Like many other western states, New Mexico adopted a modified version of the American rule (see Chapter 1) for defining legal rights to groundwater. New Mexico's adaptation of the rule restricted a land owner to use of groundwater underlying his property in a "manner reasonable to the needs of his own tract with due regard to the rights of others whose lands overlay the same aquifer," and required the land owner to prove that the groundwater he wished to "divert" derived from a subterranean stream instead of from "diffused percolating waters." [29]

[28]Ibid, pp. 597-598.

[29]Clark, pp. 233-234.

In 1927, New Mexico passed the first groundwater appropriation law in the country. This concise statement declared all natural waters with ascertainable boundaries to be public and subject to appropriation for beneficial uses. It also authorized the state engineer to supervise and control all underground waters and their appropriations.[30] Although this law went through some revisions and clarifications over the next decade (1931 statute and the act of 1931), the basic authority to regulate only those groundwater resources with ascertainable boundaries led to the state engineer's long-standing practice of declaring basins for appropriation. Prior to being declared as a basin by the state engineer, the groundwater in that basin is considered private, belonging to the individual who uses it in a beneficial manner on his own land. Once the basin is officially declared, all groundwater appropriations must be approved by an application process through the state engineer's office. Pumping from wells within declared basins is then subject to restriction by the state engineer as necessary to protect senior rights.[31]

Today, surface water rights holders continue to supplement their surface water supplies with groundwater pumped from private wells. The bench-mark case *Albuquerque* v. *Reynolds* in 1962 set the precedent for the now famous "offset" policy of New Mexico. In that case, the state engineer, S. E. Reynolds, approved the city of Albuquerque's application to drill four wells contingent on three conditions: 1) that the city measure the amount of water it pumped, 2) that it measure its return flow, and 3) that it "retire its existing rights to consumptive use of surface water to the extent necessary to offset the effects of the groundwater appropriation on the river's flow."[32]

[30]Ibid, p. 237.

[31]Ibid, p. 237-242.

[32]Ibid, p.312.

Although Albuquerque protested the conditions of Reynolds' approval and the case was not settled immediately, it finally held and remains an important facet of New Mexico water law. Currently, anyone applying for a permit to pump groundwater from a region where that pumpage would affect the rights of downstream surface water rights must purchase and retire the downstream surface water rights equivalent to the damage his pumping would incur. Unfortunately, quantifying the precise impact of pumping on downstream users is not easy, and consequently, the state engineer is often forced to make a subjective decision regarding the compensatory measures required.

2.1.4 Model

While all of the prior appropriation cases mentioned above have unique and interesting features, this study focuses on GASP. The GASP system encompasses the general features of prior appropriation system and further provides a unique example for handling the inherent problems of interference between ground-water and surface water users. The other two systems described above present difficulties in terms of computer simulation. Simulation of the Fort Morgan system would require an optimization procedure to determine and modify the rule sets over time as the physical and economic conditions changed. New Mexico water law operated successfully for many years primarily under the expertise of its late state engineer, Steve Reynolds, without any formal guidelines.

As a system which operates in response to a certain condition, namely a senior call on the river, GASP provides a simple, yet illustrative basis for constructing a computer model. This study generalizes the GASP conjunctive management system into a hypothetical management model called **GSIM** and simulates the operation of

GSIM with a computer program of the same name. Figure 1 illustrates the decision processes of the GSIM model. The model's rules for delivering surface water to rights holders follow directly from the prior appropriation doctrine. A few additions and simplifications to the real systems have been made for the purpose of making a descriptive, yet characteristic computer model. First, each surface water right holder (hereafter referred to as a diverter) also operates his own ground-water well. Each diverter's demand for water is based on the cost of water (both surface and groundwater). The amount of groundwater a diverter pumps depends on the extent to which his surface water right is fulfilled, and on the volumetric cost of groundwater as well as the cost of lifting groundwater from the water table to the ground surface (lift cost) at his well. Second, one or more supplemental water supply wells may be located upstream of all diverters. These wells represent a part of GASP's augmentation plan, which also leases upstream storage and surface water rights for the purpose of supplementing surface water supplies. Third, GSIM includes an upstream surface water reservoir for the purpose of supplementing surface water supplies.

GSIM Flowchart

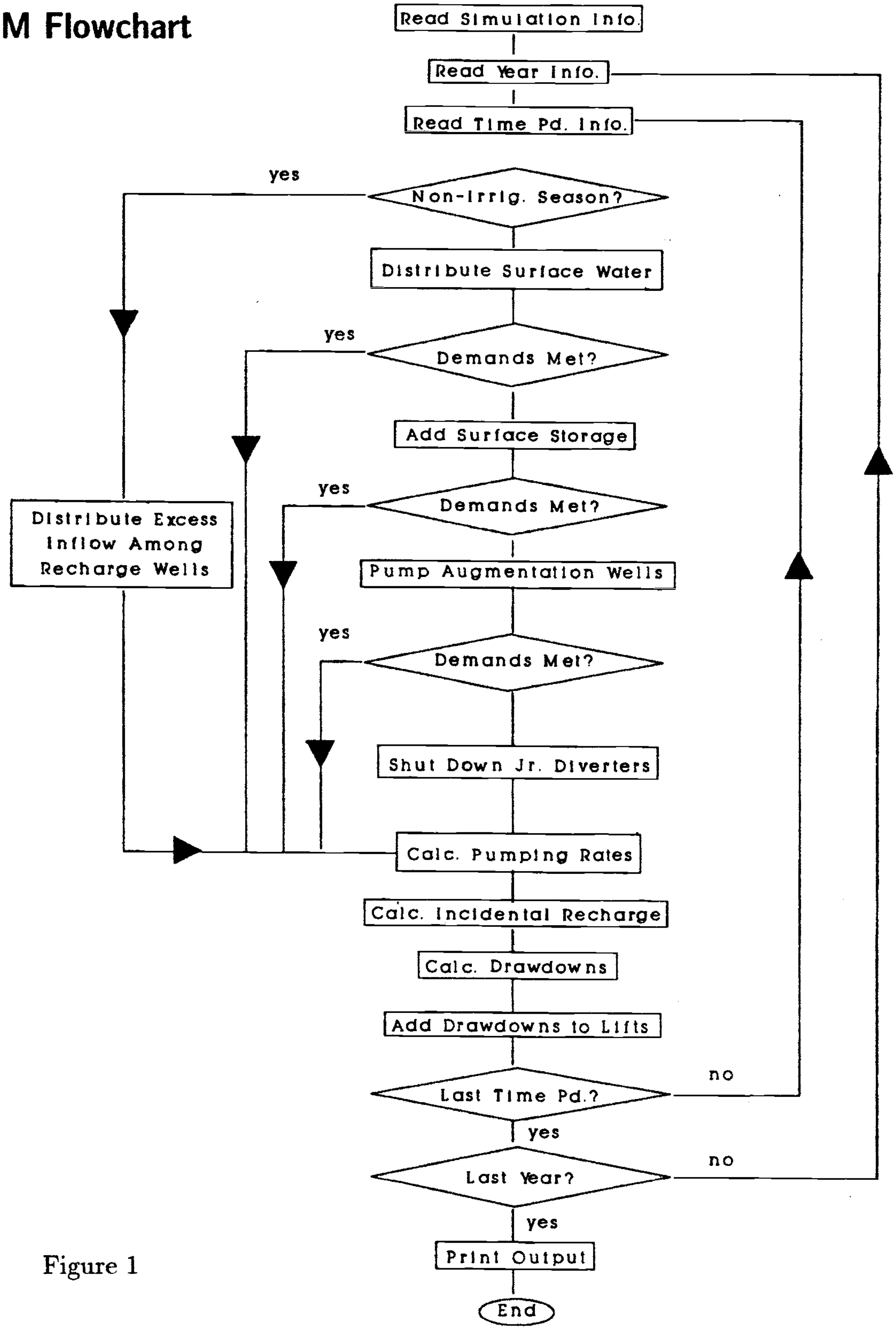

Figure 1

2.2 ADMINISTRATIVE ALLOCATION SYSTEM

As populations increase in the west, urban and industrial uses consume an increasing proportion of available water resources relative to agricultural uses. Two California regions, Santa Clara Valley and Orange County, have operating conjunctive management systems very different from the appropriation-based systems of Colorado's South Platte. Ground-water exploitation in both of these areas began as a means of sustaining agriculture, but since World War II, municipal and industrial uses have replaced farming as the primary consumptive uses of groundwater. Agriculture in Santa Clara County still accounts for roughly 10% of its total water consumption[33], while only 6% of Orange County's total water use is by agriculture.[34]

California adopted a dual system of water rights with the California Supreme Court's decision in *Lux v. Haggin* in 1886. In its decision, the Court made the controversial declaration that federal land grants did carry with them riparian rights unless the grant expressly withheld them. Consequently, the state essentially acknowledged riparian rights as "superior to all appropriation rights, except where the appropriation pre-dates the federal patent."[35] The Desert Lands Act of 1877 finally put the issue to rest, however, by indicating that all non-navigable waters on lands granted by the federal government to individuals "should be reserved for the use of the public under the laws of the states and territories named."[36] Thus, federal land grants were no longer assumed to carry with them riparian rights.

Like its approach to surface water, California also took an unconventional path

[33]"The Water Utility Enterprise", 1991, Santa Clara Valley Water District.

[34]Orange County Water District, 1990, "1988-89 Engineer's Report."

[35]Sax and Abrams, p. 310.

[36]Ibid, p. 315.

in ground-water administration with its adoption of the *correlative rights doctrine.* California does recognize the appropriation doctrine for "surplus" waters, but in the event of shortage, these rights are subordinate to correlative rights. The correlative rights doctrine, stemming from the case of *Katz v. Walkinshaw* (1903), is similar in many respects to the riparian doctrine of eastern states and can be described with three basic tenants: 1) all owners of land overlying the aquifer share the right to use the groundwater stored therein; 2) the groundwater must be used on the overlying tract and the use must be reasonable in regard to the uses of the other land owners and the characteristics of the aquifer; and 3) the groundwater user's right is usufructuary. Any surplus water, above and beyond that used on the overlying tract, that is pumped for export is administered under the prior appropriation doctrine. In times of shortage, the the available water is apportioned among the several users. The correlative doctrine does not specify the means for dividing the shortfall equitably among the rights holders. In practice, reductions are usually carried out in a *pro rata* manner based on the previous withdrawals of the user.[37]

2.2.1 Santa Clara Valley Water District, California

Santa Clara County lies just south of the San Francisco Bay, in west-central California. Currently, the majority of the 1.5 million people in Santa Clara County reside in the northern municipal/industrial region of the county. A smaller percentage of the population in the southern part of the county represents a more balanced municipal and agricultural sector. Since the 1970's, Santa Clara County, California has seen a steady decline in farming coincident with a continuous conversion of irrigated lands to urban lands. The distribution of groundwater versus surface water

[37]Sax and Abrams, pp.793-795.

consumption, however, differs considerably between urban and agricultural uses. In the 1989-90 decade, while municipal and industrial uses accounted for nearly 90% of total water use in the county, groundwater comprised only 36% of that volume. The rural areas in the southern part of the county consumed roughly 10 percent of all of the water used in the county, but 98% of that came from groundwater.[38]

The Consolidation Act of 1968 merged the Santa Clara Valley Flood Control and the Conservation Districts and in 1974, the merged districts were renamed the Santa Clara Valley Water District. The Santa Clara Valley Water District (SCVWD or the District) currently manages the surface and groundwater supplies for the entire county, and has a mandate to "reduce flood hazards, conserve local water resources, and provide adequate water supply... to meet the current and future needs of Santa Clara County" as well as to maximize the "efficient, appropriate use and reuse of water, while minimizing costs, environmental impacts, and other undesirable effects."[39] In order to address these goals, the SCVWD has implemented several programs including water pricing incentives artificial recharge, and legal restrictions on drawdowns to reduce consumption and limit drawdown.

Sea water intrusion into the groundwater system and land subsidence pose serious threats to the Santa Clara Valley area. As a preventative measure, the SCVWD monitors the water levels in over 200 wells at least every 3 months to ensure that none drop below a certain "critical" level.[40] This critical threshold is determined by the District as that minimum head (or maximum drawdown) level required to prevent

[38]Todd, D. K., 1987, "Groundwater Management in Santa Clara Valley", Santa Clara Valley Water District.

[39]Santa Clara Valley Water District,1990, Urban Water Management Plan.

[40]Ibid.

water quality diminution and land subsidence. Because the groundwater basins in the county have not been adjudicated, groundwater users may pump as much water as they can put to a beneficial use in accordance with California's correlative rights doctrine. If, however, drawdown in a particular area approaches the critical level, the District may take action to reduce or eliminate pumping in wells contributing to the excessive drawdown until the situation is remediated. In general, every effort is made to mitigate overdraft in a critical area of the aquifer by either increasing the cost of pumping or by recharging water near the pumping well.[41]

The SCVWD has successfully reduced drawdowns in the county by 75% from their 1965 levels. Much of this reduction can be credited to the District's recharge activities. The District schedules releases from its reservoir system to meet water demands and to maximize total groundwater recharge. Any water left after all demands have been met is recharged to areas with the greatest need (i.e., lowest water table). Thus, the water table has been raised enough to mitigate sea water intrusion and to prevent land subsidence while still meeting the demand for groundwater.[42]

In January 1991, the effects of a long-term drought forced the District to suspend its recharge practices in order to meet demands. The Santa Clara Valley Water Conservation Act requires that, in the event of a shortfall in surface water supplies (due to drought), the District first eliminate recharge and cut back on untreated water to agriculture before curtailing treated water to retailers (municipal users). If, after these reductions, treated water demands are still unmet, the District may reduce all treated water deliveries by an equal percentage. This drastic measure has not yet been

[41]Personal communication by Susan Hamilton (DHWR, Univ. of AZ) with Santa Clara Valley Water District, May 1991; and General Counsel of the Santa Clara Valley Water District, 1991, District Authority to Regulate Water Usage, Agenda Memorandum no. 10.

[42]Ibid.

necessary due to conservation efforts by local water users.[43]

2.2.2 Orange County Water District, California

Orange County lies south of Los Angeles County along the southern California coast. By 1920, Orange County had already begun the transformation from an agricultural- to an industrial-based economy. With roughly 50% of the population in urban areas, the County had already recognized the increased demand for groundwater as a problem. A series of droughts beginning in 1923 exacerbated the water problems of the area. By 1925, a county-sponsored study of the Coastal Plain found a rapidly declining water table and discovered sea water intrusion occurring in some places. In 1927, the Orange County Flood Control District and the Water Conservation Association were formed to conserve storm flows and to recharge water in spreading basins upstream of Orange County, respectively. These efforts largely failed to improve the water supply situation in the face of continued droughts. Under pressure to win important litigation to bring more water into the Coastal Plain, the County formed the Orange County Water District in 1933. The District was authorized to represent the interests of land owners in the Coastal Plain in all litigation involving outsiders and to manage the groundwater basin. This mandate included the tasks of preserving the quantity and quality of the groundwater in the basin, reclaiming water for beneficial use, and conserving and controlling storm and flood waters in the District.[44]

Today, Orange County's population exceeds 2.4 million[45], and urban/industrial

[43]Ibid.

[44]Bloomquist, W., 1988, The Performance of Institutions for Groundwater Management, vol. 5, Orange County, Workshop in Political Theory and Policy Analysis, 61 p.

[45]United States National Census preliminary 1990 figures.

uses consume approximately 94% of the county's total water use, with agriculture using the remaining 6%. Groundwater makes up 52% of all urban water supplies, and 38% of all water used in agriculture.[46] The Orange County Water District (OCWD or the District) still manages the groundwater basin underlying the county, and has determined its primary goal as providing "local groundwater producers a reliable, adequate, high quality water supply at a reasonable cost."[47]

Unlike the Santa Clara Valley Water District, much of Orange County has been adjudicated (i.e., groundwater rights established), so the OCWD cannot enforce any restrictions on pumping. Instead, the District encourages conservation among groundwater pumpers with a Basin Production Percentage (BPP) plan and price incentives prescribed by a Replenishment Assessment (RA) and a Basin Equity Assessment (BEA). The Basin Production Percentage is the ratio of groundwater to total water used multiplied by 100. The OCWD sets a goal BPP, and requests that groundwater producers keep their groundwater to total water ratio under that limit. The Replenishment Assessment comes in the form a tax levied by the OCWD on every acre-foot of groundwater produced. The RA is designed to provide funds to purchase enough water to "offset the average annual overdraft of the past five years plus an additional amount of water to offset $1/10^{th}$ of the accumulated overdraft."[48]

Municipal/industrial groundwater uses are taxed at a rate double that of the tax on groundwater used for agricultural purposes. The Basin Equity Assessment is designed to equalize the water costs of groundwater producers in the District. This

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[46]1988-89 Engineer's Report.

[47]Orange County Water District, 1990, "Groundwater Management Plan".

[48]Orange County Water District, 1990, personal communication by Susan Hamilton (DHWR, Univ. of AZ).

measure rewards those who reduce their groundwater consumption and purchase more expensive Metropolitan Water District water, and taxes those who pump a higher proportion of their total water from the basin. In essence, those who pump more than the prescribed BPP end up paying the same amount as the equivalent amount of imported water would have cost.[49]

The Metropolitan Water District (MWD) supplies imported surface water to much of Orange County. In a manner analogous to the OCWD's policy for groundwater, the MWD generally tries to avoid any shortfalls in surface water deliveries by encouraging conservation with pricing incentives. In the event of an extreme shortage, the MWD would curtail deliveries to irrigators before reducing those to municipalities and industries.[50] Since February 1991, the MWD has enlisted a policy of cutting back agricultural deliveries by 50% before reducing urban deliveries by up to 20%.[51] The MWD exercises as so-called "Emergency Class" water charge of three times the normal cost for excessive water requests. The result of the conservation of surface water by the MWD's customers, however, has been an increase in their groundwater pumping to make up for the reduced surface water deliveries.[52]

Orange County actively recharges water to the aquifer with injection wells in regions threatened by sea water intrusion and with recharge basins in the northwestern section of the county. The OCWD redirects flow in the Santa Ana River to its recharge

[49]1988-89 Engineer's Report.

[50]Getches, D. H., 1991, Water Allocation During Drought in Arizona and California: Legal and Institutional Responses, University of Colorado School of Law.

[51]"Incremental Interruption and Conservation Plan", 1991, Metropolitan Water District of Southern California handout.

[52]Metropolitan Water District of Southern California, 1990, The Regional Urban Water Management Plan for the Metropolitan Water District of Southern California; and personal communication by Susan Hamilton with MWD, 1991.

facilities and reserves the right to store surface water in Irvine Lake, which may then be released and recharged at the Santiago Creek facilities.[53]

2.2.3 Model

The Santa Clara Valley and Orange County systems described above have been simplified and generalized into two similar but distinct computer models for the purposes of this study. Figure 2 illustrates the structures of the models derived from the Santa Clara Valley system, **SSIM,** and from the Orange County system, **OSIM**. SSIM captures the basic operational rules that make up the Santa Clara Valley Water District's conjunctive management plan, and OSIM incorporates the significant features that distinguish Orange County's system from that of Santa Clara County. For example, both systems incorporate a price incentive for decreased pumping as drawdowns increase, but only SSIM permits the forceful shutting down of a pumping well in the event that the critical head level is breached. By contrast, OSIM requires the mandatory recharge of a certain proportion of incoming surface water, regardless of the ability of the system to meet all surface water demands, while SSIM recharges only excess water remaining after all surface water demands have been met. Both models incorporate a different water price structure for agricultural and urban uses, but the price difference between the two uses is greater in OSIM than in SSIM. Details of the two models are given in Chapter 4.

[53] Ibid.

SSIM/OSIM Flowchart

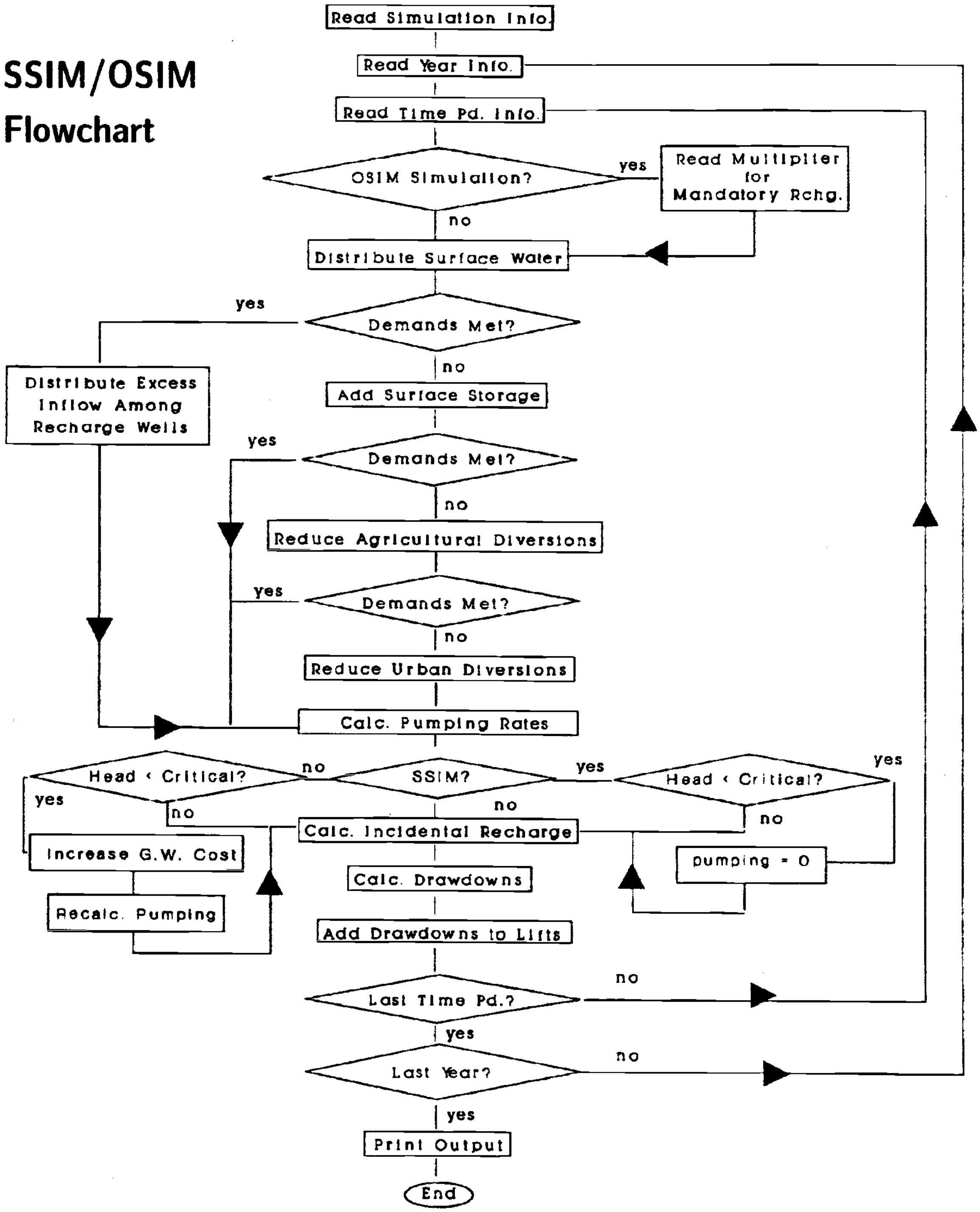


Figure 2

Chapter 3
Theoretical Consideration

3.1 RESPONSE FUNCTIONS AND CAPTURE

Response functions describe the response of an aquifer system to a unit stress (eg, pumpage). Drawdown response functions describe the drawdown at a particular location and time due to a unit pumping stress at another location and time. If $q_l(\hat{x},t)$ is the instantaneous discharge from a well at location $\hat{x}$ in the l^{th} aquifer at time t, and N_{w_l} is the number of pumping wells in the l^{th} aquifer, then the drawdown in the m^{th} aquifer at point $\hat{x}$ at time t is given by the equation,

$$s_m(\hat{x},t) = \sum_{l=1}^{M} \sum_{j=1}^{N_{w_l}} \int_o^t G_m(\hat{x},\hat{x}_{l_j},t-\tau)\ q_l(\hat{x}_{l_j},\tau)\ d\tau \qquad (1)$$

for all $\hat{x} \in D_m$ where,

M is the number of aquifer layers;

D_m is the domain of the m^{th} aquifer layer; and,

$G_m(\hat{x},\hat{x}_{l_j},t-\tau)$, $m = 1,\ldots,M$ are the instantaneous drawdown response functions.[54]

Consider a design horizon consisting of N_e consecutive stress periods. If the $q_l(\hat{x}_{l_j},t)$ is the pumpage in well j at location $\hat{x}$ in layer l at time t, and this pumpage varies from stress period to stress period but is constant within a stress period (pulse pumping), then the drawdown at the k^{th} observation point in the m^{th} aquifer layer at

[54]Maddock, T. III and L. Lacher, 1991a, Drawdown, Velocity, Storage, and Capture Response Functions for Multiaquifer Systems, Water Resources Research, vol. 27, no. 11, Nov. 1991, pp. 2887-2889.

the end of the n^{th} stress period, written as $s(m,k,n)$, is given by the equation,

$$s(m,k,n) = \sum_{l=1}^{M} \sum_{j=1}^{N_{w_l}} \sum_{i=1}^{n} \beta_d(m,k,l,j,n-i)\ q(l,j,i) \tag{2}$$

for $k = 1,\ldots,N_{O_m}$; $n = 1,\ldots,N_e$; and $m = 1,\ldots,M$, where N_{O_m} is the number of observation points for the m^{th} aquifer; $q(l,j,i) = q(\hat{x}_{l_j},j_i)$ for the j^{th} pumping point in the l^{th} aquifer; j_i is the duration of the i^{th} stress period and,

$$\beta_d(m,k,l,j,n-i) = \int_{\eta_{i-1}}^{\eta_i} G_m(\hat{x}_k,\hat{x}_{l_j},\eta_n-\tau)\ dt \tag{3}$$

The β_d's are the **drawdown response functions** and are constants independent of the quantity of pumping and drawdown (within limits of linearity). They are functions of the form of partial differential equation, the boundary conditions, the initial conditions, the model parameters and the geometry or location of the pumping. Each β_d describes the drawdown at a given location and time in response to <u>unit</u> pumping at another location and time ($i \leq n$).[55]

3.1.1 River Capture Response Functions

Capture describes the pumping-induced quantity of water gained by the aquifer from internal or boundary sources. Internal sources include rivers and hydraulically-

[55]Ibid.

connected aquifers. Boundary sources include constant-head and head-dependent boundaries. In both cases, capture is inherently a nonlinear function of drawdown, being linear with drawdown only between specified limits or bounds. In the event that these bounds are exceeded, capture is assumed to become either zero or a non-zero constant value.[56]

Figure 3 shows a conceptualization of the aquifer system modeled in this study. Capture through riverbeds and capture of decreased evapotranspiration

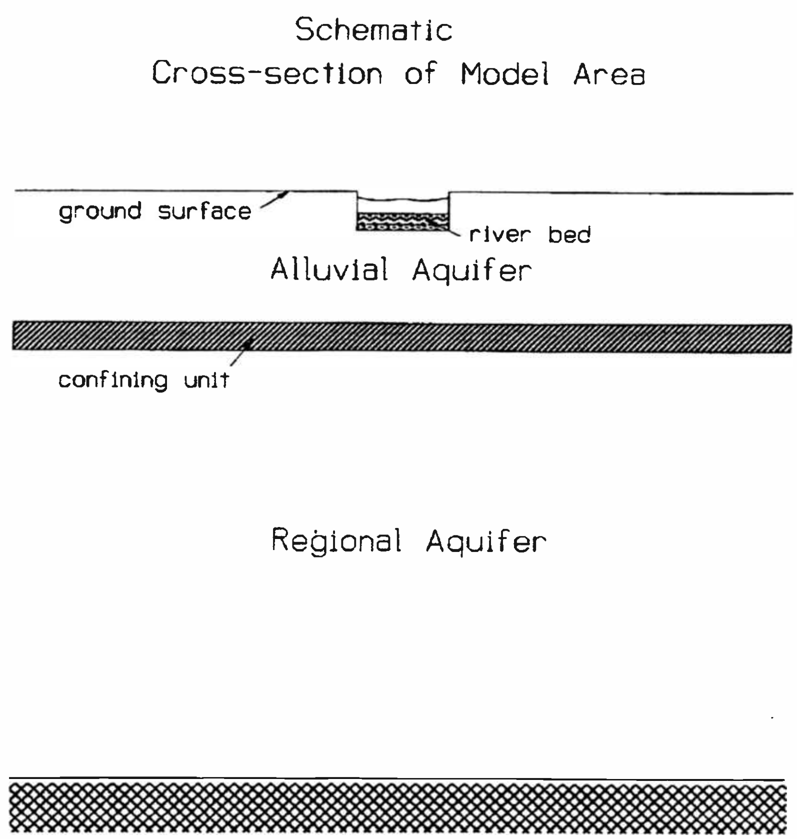


Figure 3

[56]Ibid, pp.2890-2892.

losses are assumed to occur only in the "alluvial" (unconfined) aquifer. Capture of river water by leakance into the aquifer through the bottom of a streambed requires a positive vertical head gradient between the river and the aquifer. As long as the water table lies between the river surface and the bottom of the riverbed, capture occurs as a linear function of the difference in head between the river and the aquifer. Once the aquifer head drops below the bottom of the streambed, the region below the bottom of the streambed begins to desaturate and the rate of capture becomes constant and independent of head.

Like drawdown response functions, river capture response functions can be calculated to describe the volume of water captured from a particular river reach at a certain time due to pumping in a given location at a given time. If H_d is the river stage (see Figure 4a), h_1 is the head in the aquifer under the river, h_{0_1} is the initial head, h_b is the elevation at the bottom of the streambed and b is the streambed thickness, then the vertical head gradient is defined as $(H_d - h_1)/b$ and the drawdown to the bottom of the riverbed is defined as $s_b = h_{0_1} - h_b$. The streambed is assumed to have a vertical hydraulic conductivity, K_z, and no storage properties. Furthermore, the river stage, H_d, is assumed to remain unchanged by any flow between the river and the aquifer.

For capture to remain a linear function of drawdown, h_1 must not drop below the bottom of the streambed. For this linear case, the total quantity of flow, $Q_{RT}(t)$, that leaks from through the streambed into the aquifer is given by the integral,

$$Q_{RT}(t) = \int_{\hat{x} \in \delta} c_{ps}(\hat{x}) \, [H_d(\hat{x}) - h_1(\hat{x},t)] \, d\hat{x} \tag{4}$$

where δ is the surface area of the river or stream for the entire domain, and $c_{ps}(\hat{x})$, referred to as the surface capture coefficient, is given by the relation,

$$c_{ps}(\hat{x}) = \frac{K_z(\hat{x})}{b(\hat{x})} \tag{5}$$

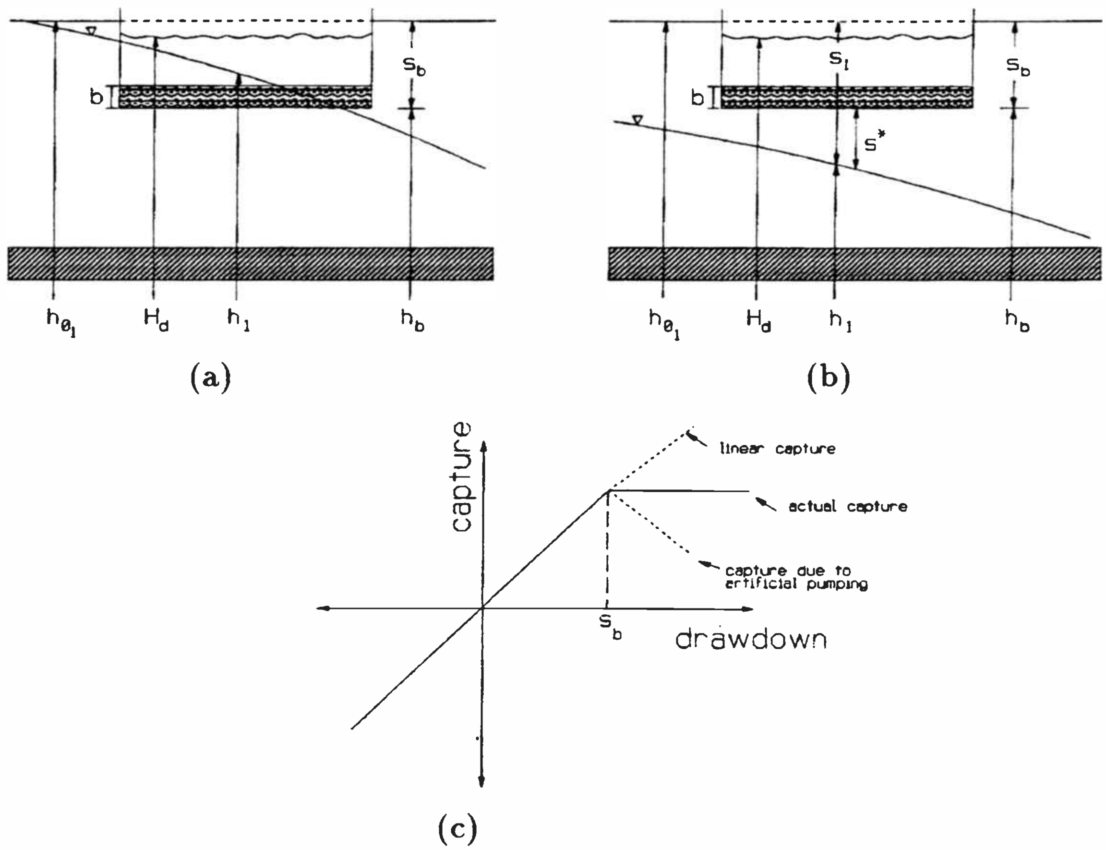


Figure 4

Capture Through a Riverbed

Replacing $h_1(\hat{x},t)$ with $h_{0_1}(\hat{x}) - s_1(\hat{x},t)$ gives,

$$Q_{RT}(t) = \int_{\hat{x} \in \delta} \frac{K_z(\hat{x})}{b(\hat{x})} \left[H_d(\hat{x}) - h_1(\hat{x},t) \right] d\hat{x} + \int_{\hat{x} \in \delta} \frac{K_z(\hat{x})}{b(\hat{x})} s_1(\hat{x},t) \; d\hat{x} \tag{6}$$

The first integral on the right side of the above equation represents the natural base flow to and from the aquifer. The second integral represents the flow captured from the river through the streambed as a result of pumping. In a manner analogous to the derivation of the drawdown response function equation, equation (6) can be rewritten for pulse pumping as,

$$Q_{RT}(k,n) = \sum_{l=1}^{M} \sum_{j=1}^{N_{w_l}} \sum_{i=1}^{n} \beta_{Q_R}(m,k,l,j,n-i)\ q(l,j,i) \tag{7}$$

for $k = 1,\ldots, N_{\delta r}$, and $n = 1,\ldots, N_e$, where $N_{\delta r}$ is the number of discrete river reaches. The β_{Q_R}'s are **stream capture response functions** which represent the quantity of flow captured through the k^{th} river reach in the n^{th} stress period due to unit pumping from the j^{th} well in the l^{th} aquifer during the i^{th} stress period *when linearity is maintained.*[57]

3.1.1.1 Nonlinear case 1.

In the event that the water table drops below the bottom of the river bed, or $h_{0_1} - h_1 > s_b$ (Fig. 4b), the region below the streambed begins to desaturate and leakance becomes constant. In that case, river capture calculated with Equation 7 would yield erroneously high values. In order to compensate for this occurrence during the computer simulation, "artificial wells" are emplaced in the surface aquifer under the river nodes and their respective response functions calculated. By activating an artificial well at precisely the rate by which the original estimate (Eq. 7) exceeds the constant (real) rate of capture, the leakance value is corrected (Fig. 4c). The artificial pumping rate for a "river well" can be calculated by iteration or by optimization (see Maddock and Lacher, 1991a for an explanation of the optimization method). The

[57]Ibid.

simulations in this study used the iterative technique. Using the notation defined earlier in this section and referring to Figure 4b, drawdown can be written as,

$$s_1 = h_{0_1} - h_1 \tag{8}$$

Then, $s^* = s_1 - s_b$ is the distance by which drawdown exceeds the depth to the bottom of the riverbed. The riverbed conductance, C_R [L^2/t], is defined by,

$$C_R = \frac{K_z L W}{b} \tag{9}$$

where L is the length of the river reach and W is the width of the reach (Fig. 5).

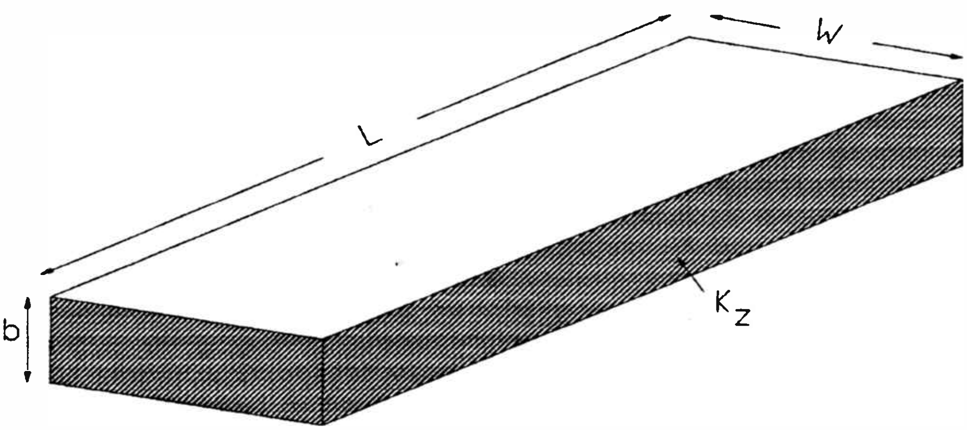


Figure 5

Conceptualization of a River Reach

The simulation programs calculate an initial estimate for the artificial pumping rate (q_{A_r}) at a "river well" by,

$$q_{A_r} = C_R \; s^* \tag{10}$$

Because this estimate is based on an erroneously large drawdown value (overestimated by the linear response function equation (Eq. 2)), and because this artificial pumping will influence drawdowns, the final value of the artificial pumping rate, q_{A_r}, must be calculated iteratively. By the same token, river capture from the node where drawdown exceeds the range of linearity is determined by the sum of the pumpages from real wells and artificial wells multiplied by their respective river capture response functions.

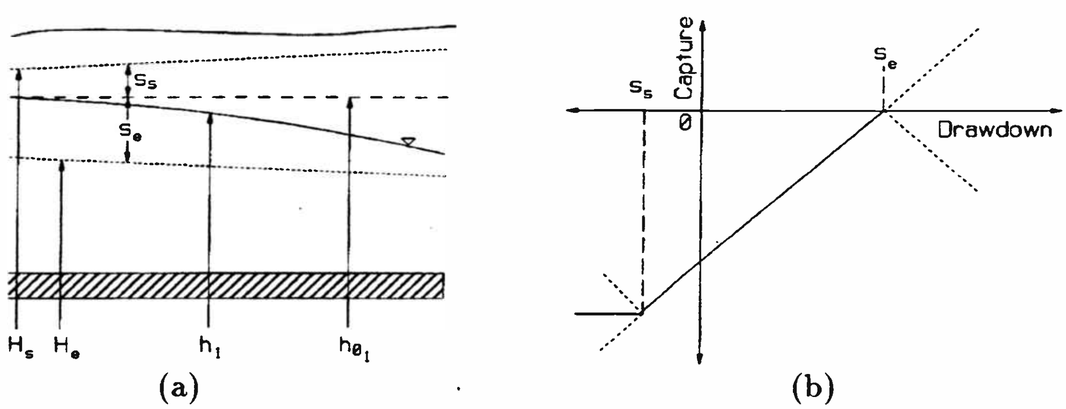


Figure 6

Evapotranspiration Capture

3.1.1.2 Nonlinear Case 2.

Limits of linearity for drawdown and capture in the aquifer system must also be calculated for each evapotranspiration node. Through evapotranspiration, plants provide a conduit for transmitting water out of the aquifer and into the atmosphere. The following discussion refers to the illustrations in Figures 6a and 6b. As long as the head in the aquifer, h_1, remains above the evapotranspiration (ET) extinction depth, H_e, and below the maximum ET surface, H_s, then the evapotranspiration rate is a linear function of head in the aquifer. If, however, h_1 falls below H_e, evapotranspiration ceases, and the rate is therefore independent of head. Similarly, in the event that h_1 rises above H_s, evaporation occurs at the maximum possible rate (R_e) in accordance with the vegetation and climatic conditions, and is again independent of head (Figure 6b).

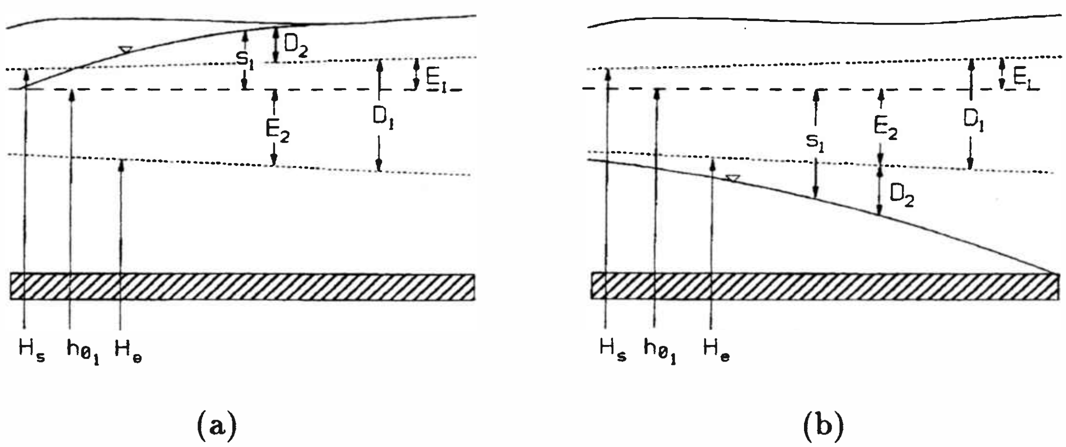


Figure 7

Non-linear Evapotranspiration Capture Conditions

For a particular ET node, define the following terms (see Figures 7a and b):

$$E_1 = h_{0_1} - H_s \tag{11}$$

$$E_2 = h_{0_1} - H_e \tag{12}$$

$$D_1 = E_2 - E_1 \text{ (where } E_1 \text{ is negative)} \tag{13}$$

$$D_2 = \begin{cases} s_1 - E_1, & s_1 < E_1 \quad \text{(Fig. 7a)} \\ s_1 - E_2, & s_1 > E_2 \quad \text{(Fig. 7b)} \end{cases} \tag{14}$$

Then, the initial estimate for pumping in the artificial well at the ET node in question is given by,

$$q_{A_e} = \left(\frac{R_e}{D_1}\right) \cdot D_2 \tag{15}$$

As in the case of pumping in artificial river wells, the final pumping rate, q_{A_e}, is calculated iteratively.

3.1.2 Incorporation of Response Functions

Prior to calculating the response functions, the steady-state head configuration for a hypothetical aquifer system is generated using the United States Geological Survey (U.S.G.S.) computer program, MODFLOW (Modular Three-dimensional Finite-difference Ground-water Flow Model).[58] The MODFLOW general head boundary package is used in lieu of the stream or evapotranspiration packages in the steady-state analysis to insure linearity. The MODFLOW stream and evapotranspiration packages are inherently nonlinear. MODRSP.[59] is used to calculate the response functions for storage; velocity; and capture from streams, evapotranspiration, and prescribed head or head dependent boundaries. For the purposes of this study, only drawdown and river capture response functions were generated. MODRSP generates tabular output files

[58]McDonald, M. G., and A. W. Harbaugh, 1988, A Modular Three-dimensional Finite-difference Ground-water Flow Model, USGS Open-file Report 83-875.

[59]Maddock, T. III and L. J. Lacher, 1991b, MODRSP: A Program to Calculate Drawdown, Velocity, Storage and Capture Response Functions for Multi-Aquifer Systems, Dept. of Hydrology and Water Resources Publication HWR No. 91-020, University of Arizona, 235 p.

which generally require conversion to matrix form for further manipulation. Figure 8 illustrates the symmetric structure of a response function, or *beta*, matrix. One such matrix must be generated for each set of response functions produced by MODRSP. These matrices tend to be very large (on the order of 20 Mbytes), so the user is urged to select only the necessary set of response functions for the problem at hand.

During each time period, the simulation program calculates and stores new pumping rates for all pumping wells, both artificial and real. At the end of each time period, these and all prior pumping rates (up to the time current time period) are multiplied by their respective response functions and summed to calculate new drawdowns and river capture values for nodes of interest. The principal advantage of this method for evaluating the system's condition at the end of each time period is that the response functions for a particular system need only be calculated and read by the simulation routine once, regardless of the total number of time periods in the scenario or the total number of scenarios simulated. Furthermore, the response functions need only be calculated once for the simulation of a variety of different management scenarios. Of course, this condition requires that the system configuration (pumping well, evapotranspiration, river node locations, etc.) remains constant throughout the simulation.

3.2 SUPPLY AND DEMAND

For each user, the *total demand* for water can be calculated by:

$$D_i = A(P_i)^\alpha \tag{16}$$

where,

	$q(111)\ldots$	$q(1N_{w_1}1)\ldots$	$q(L11)\ldots$	$q(LN_{w_L}1)\ldots$	$q(11n)\ldots$	$q(1N_{w_1}n)\ldots$	$q(L1n)\ldots$	$q(LN_{w_L}n)$
$s(111)$	$\beta(11110)\ldots$	$\beta(111N_{w_1}0)\ldots$	$\beta(11L10)\ldots$	$\beta(11LN_{w_L}0)$	0	0	0	0
$s(1N_{o_1}1)$	$\beta(1N_{o_1}110)\ldots$	$\beta(1N_{o_1}1N_{w_1}0)\ldots$	$\beta(1N_{o_1}L10)\ldots$	$\beta(1N_{o_1}LN_{w_L}0)$	0	0	0	0
$s(M11)$	$\beta(M1110)\ldots$	$\beta(M11N_{w_1}0)\ldots$	$\beta(M1L10)\ldots$	$\beta(M1LN_{w_L}0)$	0	0	0	0
$s(MN_{o_M}1)$	$\beta(MN_{o_M}110)\ldots$	$\beta(MN_{o_M}1N_{w_1}0)\ldots$	$\beta(MN_{o_M}L10)\ldots$	$\beta(MN_{o_M}LN_{w_L}0)$	0	0	0	0
$s(11n)$	$\beta(1111n\text{-}l)\ldots$	$\beta(111N_{w_1}1n\text{-}l)\ldots$	$\beta(11L11n\text{-}l)\ldots$	$\beta(11LN_{w_L}n\text{-}l)\ldots$	$\beta(11110)\ldots$	$\beta(111N_{w_1}0)\ldots$	$\beta(11L10)\ldots$	$\beta(11LN_{w_L}0)$
$s(1N_{o_1}n)$	$\beta(1N_{o_1}11n\text{-}l)\ldots$	$\beta(1N_{o_1}1N_{w_1}n\text{-}l)\ldots$	$\beta(1N_{o_1}L1n\text{-}l)\ldots$	$\beta(1N_{o_1}LN_{w_L}n\text{-}l)\ldots$	$\beta(1N_{o_1}110)\ldots$	$\beta(1N_{o_1}1N_{w_1}0)\ldots$	$\beta(1N_{o_1}L10)\ldots$	$\beta(1N_{o_1}LN_{w_L}0)$
$s(M1n)$	$\beta(M111n\text{-}l)\ldots$	$\beta(M11N_{w_1}1)\ldots$	$\beta(M1L1n\text{-}l)\ldots$	$\beta(M1LN_{w_L}n\text{-}l)\ldots$	$\beta(M1110)\ldots$	$\beta(M11N_{w_1}0)\ldots$	$\beta(M1L10)\ldots$	$\beta(M1LN_{w_L}0)$
$s(MN_{0_M}n)$	$\beta(MN_{o_M}1n\text{-}l)\ldots$	$\beta(MN_{o_M}1N_{w_1}n\text{-}l)\ldots$	$\beta(MN_{o_M}L1n\text{-}l)\ldots$	$\beta(MN_{o_M}LN_{w_L}n\text{-}l).$	$\beta(MN_{o_M}110)\ldots$	$\beta(MN_{o_M}1N_{w_1}0)\ldots$	$\beta(MN_{o_M}L10)\ldots$	$\beta(MN_{o_M}LN_{w_L}0)$

Figure 8

Structure of Response Function Matrix

$D_i =$ demand for time period i

$A =$ calibration constant

$P_i =$ price of water in time period i

$\alpha =$ price elasticity of demand[60]

The computer simulation programs calculate the calibration constant, A, for each type of user (groundwater only or mixed surface and groundwater) according to the following rules:

For groundwater users:

$$A = Q_{g_o}/(P_o)^{\alpha} \tag{17}$$

where,

$P_o =$ $C_g + CE =$ initial cost of pumping groundwater

$C_g =$ cost per unit volume of groundwater

$CE =$ energy cost associated with lifting water from water table to ground surface

$Q_{g_o} =$ amount pumped (may equal pumping capacity of well) per unit time

For surface water users:

$$A = R/(P_o)^{\alpha} \tag{18}$$

[60]Price elasticity of demand (α) is an economic measure of how a change in price of a product will affect the quantity demanded. In general, it is the ratio of the percentage change in quantity of a product demanded to a given percentage change in price. Since a price increase generally results in a demand decrease, α is usually negative, and the larger $|\alpha|$, the more elastic the demand. (see Haeussler, E. F. Jr., and R. S. Paul, 1980, Introductory Mathematical Analysis for Students of Business and Economics, Reston Publishing Company, Inc., pp. 373-375, for example).

where,

$P_o = C_s =$ initial surface water cost

$R =$ volumetric water right.

Once the calibration constants are determined, the simulation programs calculate pumping rates for all users as follows:

For groundwater users:

$$Q_g = D_{P_i} \tag{19}$$

where,

$Q_g =$ groundwater pumping in time i ($\leq \bar{Q}_g$)

$D_{P_i} =$ total water demand at price P_i

$\bar{Q}_g =$ volumetric groundwater right;

For combined surface/groundwater users:

$$Q_g = \begin{cases} D_{P_i} - Q_s, & D_{P_i} > Q_s \\ 0, & otherwise \end{cases} \tag{20}$$

where,

$Q_s =$ surface water diversion

$Q_g =$ groundwater pumping in time i ($\leq \bar{Q}_g$)

$\bar{Q}_g =$ volumetric groundwater right.

Chapter 4
Simulation Programs and Models

4.1 MANAGEMENT MODELS

As stated in Chapter 1, the primary purpose of this study is to develop and implement a tool for comparing the relative performances of three different management schemes under various circumstances. Such a comparison, however, must be distinguished from a subjective evaluation of systems that evolved under different hydrogeologic and socio-political environments. The "goodness" of a particular management system is only defined for a given set of evaluative criteria and by the values of those concerned. The residents of an area may agree, for example, that minimizing drawdowns is their top priority, or they may depend very heavily on surface water and therefore put surface water deliveries at a higher premium than minimal drawdowns. In either case, the performance of their management system could be tested under many different circumstances. The following list suggests a few scenario variables for exploring the performance of a given conjunctive management policy rule set:

- number of users in the system;
- spatial orientation of senior versus junior users (see explanation of prior appropriation doctrine below);
- surface water availability;
- water rights (allocations);
- pumping lift costs;
- distribution of agricultural vs. municipal users;
- hydraulic transmissivity distribution;

- river-bed conductances and river-bed thicknesses;
- maximum evapotranspiration rate, extinction depth and maximum evapotranspiration surface values;
- hydrologic boundary conditions;
- return flow as proportion of total water used;
- infiltration rates;
- price elasticity of demand.
- base price of ground water for a given depth to water table;
- threshold and critical head levels (see explanation under "SSIM and OSIM Models in Detail");
- surface water outflow requirements;
- mandatory recharge rates;

and,

- replacement water supply provision (GSIM only).

The simulations in this study explore the impacts that changes in some of these variables have on the performances of the three conjunctive management systems described in the "Focus of Study" section in Chapter 1.

4.2 SIMULATION PROGRAMS

The computer programs employed in this study have inherent limitations and restrictions. In order to make meaningful models with the programs, the user must understand and consider the underlying assumptions of each program.

4.2.1 MODRSP

Maddock and Lacher[61] outline the assumptions and aquifer characteristics required for the computer calculation and subsequent implementation of response functions. In addition to those mentioned in the preceding discussion, MODRSP requires/allows that:

- The aquifers underlying the model area are hydrologically connected;

- The saturated thickness in each of the aquifers is large in comparison with any drawdown that might occur within that aquifer, and hence each aquifer's transmissivity is independent of head;

- The boundaries for each aquifer may be irregular in shape. Aquifer boundaries need not be congruent amongst the layers;

- The transmissivity may be non-homogeneous and anisotropic; storativity may be non-homogeneous;

- There is no land subsidence and water is instantaneously released from storage. The storativity is independent of time and hydraulic head. The confining layers have no storage qualities;

- Pumping from a well may vary from stress period to stress period, but not within a stress period.

[61] Maddock and Lacher, 1991a,b.

4.2.2 GSIM, OSIM and SSIM[62]

The following conditions, categorized by *scenario variables*, apply to all three simulation programs:

- The simulation program reads the *total inflow* to the system in discrete volumes for each time step within each year. All surface water is assumed to enter the system at one point in the grid area;

- *Required surface water outflow* for the system is read for every time step. The system outflow requirement is senior to all other surface water rights;

- The volume of available *surface* (reservoir) *storage* for the system is read at the beginning of each year, and that amount of water is assumed to be available to surface water diverters during that year until it is depleted according to management rules;

- The user must provide the following *hydrologic information* (invariant for the entire simulation) to the simulation routines:
    - Steady-state head configuration;
    - ET nodes (row, column), maximum ET rate per unit area [L/t], maximum ET surface, extinction depth;
    - River nodes (row, column), riverbed bottom elevation, riverbed conductance [L^2/t];
    - x-direction node length, y-direction node length;

[62] The FORTRAN source code, input files, and sample output files are included on the floppy disk in the back pocket of this report.

- *Time step lengths* may vary within a year, but the number of time steps within any year must remain constant throughout the simulation. When numbered consecutively from the beginning of the simulation to the end, the individual time steps are referred to as time periods. For example, a model with 10 years, each consisting of two equal time steps, contains 20 time periods.

- All *diversion, pumping well, river, ET, boundary, and recharge well node locations* remain constant throughout the simulation;

- The *aquifer* system may have up to three *layers*;

- *Infiltration recharge* from irrigation occurs via injection at a hypothetical surface-layer well at the diversion node. The user specifies the fraction of the total volume of water (ground and surface water) applied at the node that will recharge;

- Ground-water users who have no surface water rights may also be present in the model area. These wells are hereafter referred to as *independent pumping wells*;

- The user specifies the volumetric *surface water right* of each diverter for each time period;

- *Initial lifts* for each pumping well in the model area must be specified by the user;

- The user must specify *well capacities* for all pumping wells;

- The *price elasticity of demand* is read at the beginning of the simulation and remains constant throughout the simulation. In OSIM and SSIM, this value may be different for agricultural and municipal users;

- Each surface water diverter has a private well to supplement his surface water allotment. The user may indicate no pumping well at a node by setting the *well capacity* to 0.00;

- The user provides *ground-water costs* in the form of a table of cost per unit volume and lift (energy) costs for various lifts for each year in the simulation;

- The programs arbitrarily calculate the cost of surface water as $\frac{1}{10}$ of the lowest volumetric groundwater cost for the first time period of the simulation. This multiplier may be altered by the user.

4.2.3 GSIM Model In Detail

As explained in the statement of purpose of this report, the GSIM model does not attempt to capture every detail of the GASP rule set, but rather, it tries to capture the major rule characteristics which distinguish it in principle from the other rule sets. In contrast to the OSIM and SSIM models, the water allocation system in GSIM operates under the principles of the prior appropriation doctrine. Under this doctrine, junior users bear the heaviest burden in the event of a surface water shortfall, while every effort is maintained to meet the demands of senior users. In addition to the features common to all three simulation programs, the following features are unique to GSIM:

- Supplemental water supply wells, or *augmentation wells*, may pump groundwater directly into the stream to supplement surface water supplies in times of shortage. The cost for operating these wells is shared by the groundwater users who benefit from them, and is not directly reflected in the model, but is included in the volumetric cost of groundwater (C_g under Equation 16);

- Augmentation wells must lie upstream of all diverters, and are pumped, as needed, up to their specified capacities according to their order in the GSIM data input file;

- No distinction is made between the values for elasticity of demand for urban and agricultural/municipal water users;

- In the event of a surface water shortfall, after supplementation via augmentation wells and reservoir storage, individual users will be required to reduce or halt their diversions in order of most junior to most senior. Each junior will be "shut down" until the demands of all users of higher rank have been satisfied or until all users have been shut down. Any restriction on a user's diversion applies for one full time step;

- Intentional recharge occurs only in <u>non-irrigation</u> seasons, when no diversions occur and no pumping occurs at diversion nodes. Any inflow exceeding the outflow requirement for the time period is recharged first into the recharge well with the lowest head until that well's capacity is reached, then into the recharge well with the next lowest head, and so on. If no recharge wells exist, all inflow exits the system during non-irrigation seasons. Although GASP has no artificial recharge provision, this feature is part of the Ft. Morgan system, and represents an additional component of conjunctive management.

4.24 SSIM and OSIM Models in Detail

Like GSIM, the SSIM and OSIM models incorporate many simplifications to the "real world" systems in Santa Clara Valley and Orange County. Instead of operating under a priority system, the SSIM and OSIM models illustrate the administrative allocation systems in place in California. The major distinction between GSIM and the SSIM/OSIM models lies in the method for distributing surface water to users. In the event of a shortage, the administrative allocation systems distribute the shortfall among all users in a particular group (agricultural or municipal/industrial), as dictated by the management rules of the governing system. Although the OSIM and SSIM models are distinct, they are similar enough to be incorporated into one computer program with a series of *flags* in the FORTRAN code that indicate decision pathways for SSIM vs. OSIM (see Fig. 2). The following list outlines the features and input requirements common to SSIM and OSIM:

- Agricultural and urban water users may be distinguished with different values for price elasticity of demand (specified by the program user), but the rule sets of both systems specify different groundwater costs for the two kinds of users, as well as different procedures for distributing shortfalls among the two groups.

- Groundwater for agricultural use is priced at $\frac{1}{4}$ the urban cost for groundwater for a particular lift (given in price table) in SSIM. In OSIM, agricultural groundwater is priced at $\frac{1}{2}$ the urban ground-water cost;

- In times of shortage, agricultural diversions are reduced according to the following procedure:

(1) Calculate percentage by which diversion should be cut (CUT):

If **first year** of simulation, CUT = 25%.

For any **subsequent year**,

$$\mathrm{CUT} = \left|\frac{\text{last year's inflow} - \text{this year's inflow}}{\text{last year's inflow}}\right| \times 100.$$

(2) Calculate user's average delivery (AD) for the same time step over the last 3 years.

If **first year of simulation**, skip calculation.

If **second or third year of simulation,**

$$\mathrm{AD} = \left\{\sum_{i=1}^{n} \text{delivery}(i)\right\} \div n$$

where n is the number of years up to the present (i.e., 2 or 3).

Otherwise,

$$\mathrm{AD} = \left\{\sum_{i=(N\text{-}3)}^{(N\text{-}1)} \text{delivery}(i)\right\} \div 3.$$

(3) Calculate surface water delivery for user for this time step by:

$$\text{DELIVERY} = \text{RIGHT} - \text{CUT}*(\text{AD})$$

or

$$\text{DELIVERY} = \text{RIGHT}$$ (if the above equation produces a negative value);

where, DELIVERY = volume of water permitted for diversion by user in that time period

RIGHT = volumetric surface water right of user for time period.

- The groundwater cost for a given well increases sharply as the head level at that well approaches a designated *critical elevation* (specified by the user);

In SSIM, if the water table drops below the critical head elevation for that node, the rules for that system attempt to protect the area in the vicinity of the well from dangerously large drawdowns by terminating pumping for the current time period. If the water table recovers in a subsequent time period, the well is permitted to return to operation.

For the condition of drawdown at a particular node breaching the critical head level, OSIM does not ration pumping, but instead, uses incentive pricing to discourage pumping until the head level recovers.

- The user provides a *threshold* value for the proximity to which the head elevation in a given well may approach the critical head level at that node without incurring an sharp increase in groundwater cost. For the SSIM model, when the head level at a well comes within this threshold of the critical head elevation, the groundwater cost per unit volume triples (an arbitrary choice for simulation purposes) and remains that way until the head level in the well recovers back to a point above the threshold or drops below the critical head level. NOTE: this value is only used in SSIM, but a dummy value must still be read for OSIM.

- In the event that inflow satisfies all demands, excess inflow is distributed among recharge wells in the region. Available recharge water is pumped into the recharge well with the lowest head at the end of the time period until that well's maximum recharge capacity is reached. If more water is still available and more than one recharge well exists, SSIM/OSIM recharges the remaining water into the well with the next lowest head, up to its capacity, and so on. Any water left after all recharge wells have been fully utilized exits the system via the single "river" channel;

- In accordance with Orange County's policy of recharging a fraction of available surface water, OSIM reads a *mandatory recharge coefficient* at the beginning of each time period. This value is multiplied by the total inflow to the system for that time period to determine what volume (fraction of inflow) of water must be artificially recharged.

Chapter 5
Simulations

5.1 SCENARIOS

Twelve different scenarios were simulated with GSIM and SSIM/OSIM. In this study, a ***scenario*** refers to a particular configuration of scenario variables in a specific physical and policy setting. For example, scenario 1A differs from scenario 1B only by having a different hydrologic transmissivity distribution for the aquifer system; all other features of the two scenarios are the same. Figure 9 illustrates the physical configuration that applies to all of the simulations in this study:

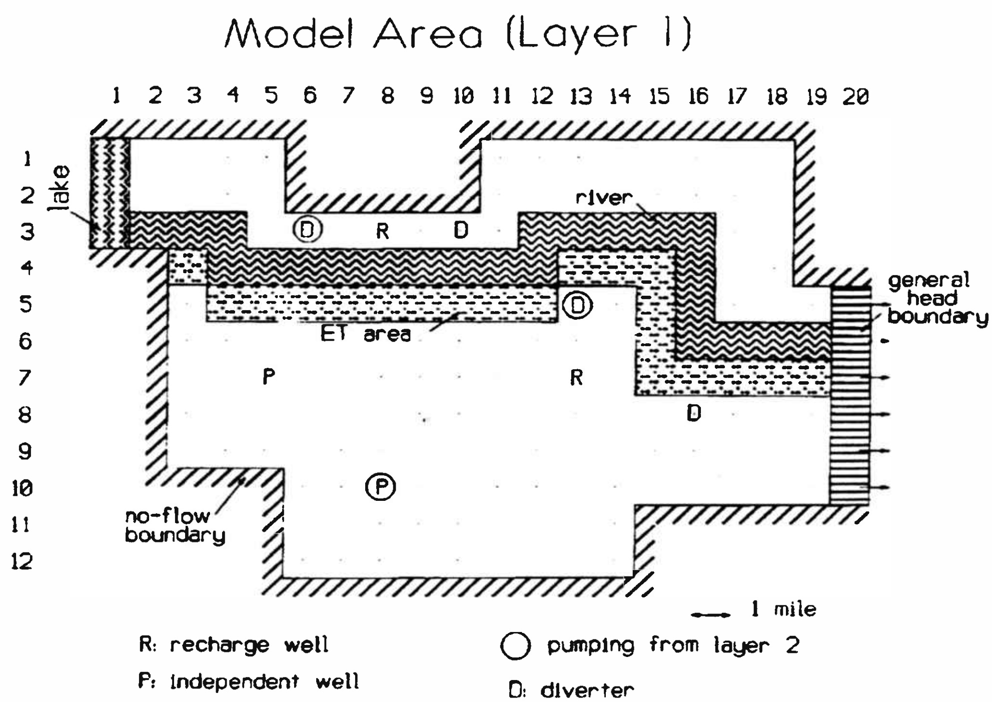


Figure 9

* four surface water diversion points.

SSIM/OSIM: two agricultural and two urban

GSIM: four agricultural

* two independent pumping well locations (unrelated to diversions, considered agricultural in these simulations).
* one augmentation well (GSIM only).
* time scale: ten years, two equal time steps per year (total of 20 consecutive time periods).

Table 1a lists the distinguishing features of each of the twelve scenarios. The key

	SSIM/ OSIM	SSIM/ OSIM	GSIM	Transmis-sivity Distrib.	Required Outflow Schedule	No Indep. Wells	TP2 Dmd. =0.0
Simulation #	α-urban	α-agric.	α				
1A	-0.5	-0.5	-0.5	1	1		
1B	-0.5	-0.5	-0.5	2	1		
1C	N/A	N/A	-0.5	1	1		
1D	N/A	N/A	-0.5	2	1		
2A	-0.5	-1.0	-1.0	1	1		
2B	-0.5	-1.0	-1.0	2	1		
4A	-0.5	-0.5	-0.5	1	1		X
4B	-0.5	-0.5	-0.5	2	1		X
5A	-0.5	-1.0	-1.0	1	1		X
5B	-0.5	-1.0	-1.0	2	1		X
6	-0.5	-0.5	-0.5	1	2		
7	-0.5	-1.0	-1.0	2	2		
8	-0.5	-0.5	-0.5	1	1	X	
9	-0.5	-0.5	-0.5	1	1	X	

Table 1a

Distinguishing features of scenarios 1A - 9.

variables in the scenarios are: 1) price elasticity of demand (α) for both urban and agricultural users, 2) transmissivity distribution in the two aquifer layers, 3) the magnitude of surface water rights and surface water outflow requirements for each time period, and 4) the presence or absence of surface water demands in time step 2 of each year, and 5) the arrangement of senior vs. junior users in the GSIM scenarios. Table 1b compares the priorities of the four diverters in the otherwise identical scenarios GSIM 1A, GSIM 1C, and GSIM 1D. The elasticity of demand

Diverter Priorities for GSIM Scenarios

GSIM1A	GSIM1C	GSIM1D
3,6 *	5,13	8,16
5,13	8,16	3,6
3,10	3,6	3,10
8,10	3,10	5,13

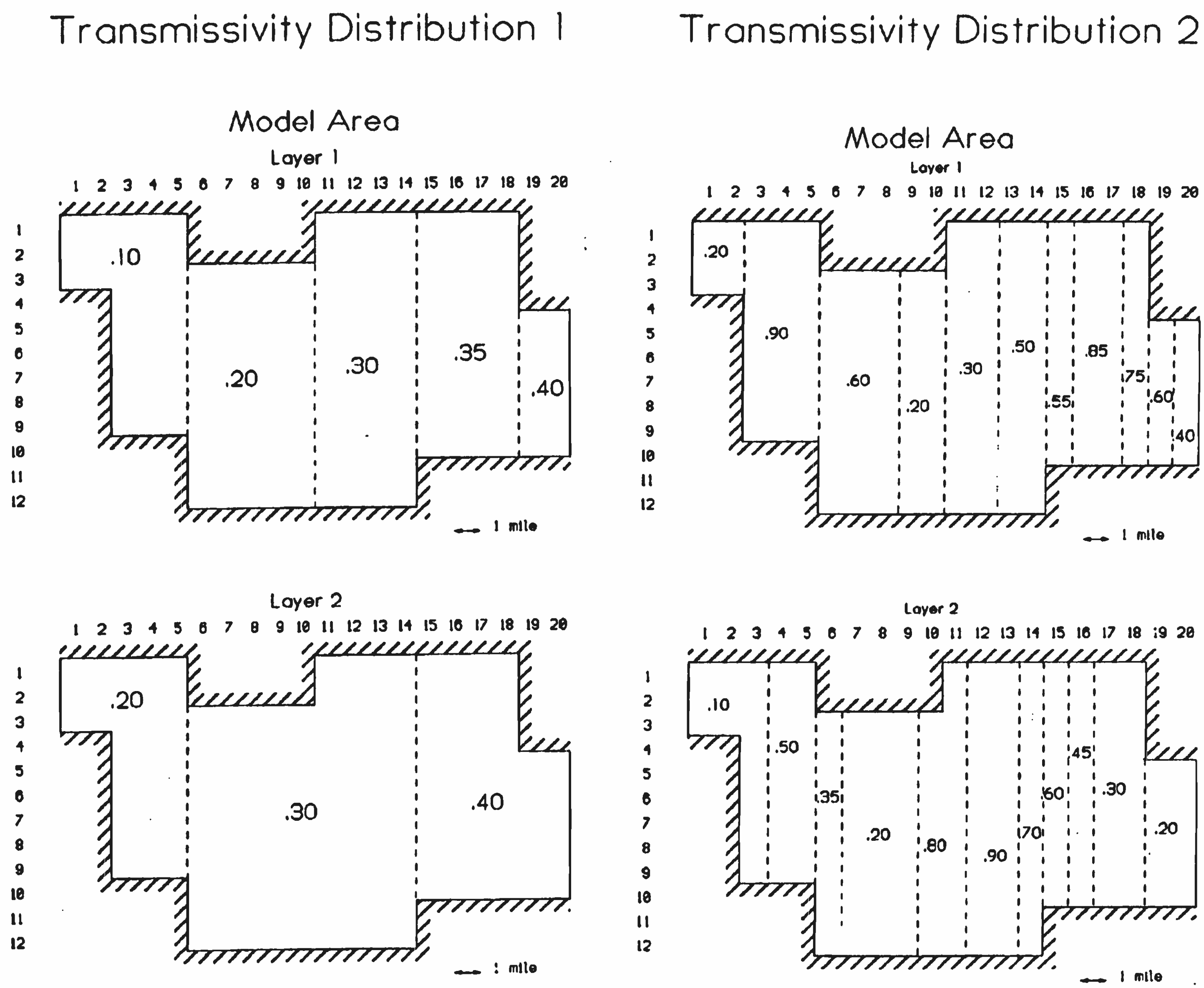
* diverter at node 1,3,6

Table 1b

Seniority of Diverters in GSIM Scenarios 1A, 1C, and 1D

(seniority decreases from highest to lowest down each column)

is either the same (-0.5) for urban and agricultural users or is set to -0.5 for urban users and -1.0 for agricultural users for each scenario. Layer 1 and layer 2 transmissivity distributions for scenarios 1A, 2A, 4A, 5A, and 6-9 are shown in Figure 10a, and Figure 10b illustrates those for scenarios 1B, 2B, 4B, and 5B. The key differences between the two distributions are: 1) an overall increase in magnitude from distribution 1 to distribution 2, and 2) and increase in zonation from the first to the second distribution. The volumetric surface water right held by each hypothetical "diverter" in the models described in this study must be specified by the model user. Tables 2a and b list the surface water rights for the four diverters in all of the scenarios.



Transmissivity Distribution 1
Transmissivity Distribution 2
Model Area
Layer 1
Layer 2
.10
.20
.30
.35
.40
.20
.30
.40
.20
.90
.60
.20
.30
.50
.55
.85
.75
.60
.40
.10
.50
.35
.20
.80
.90
.70
.60
.45
.30
.20
1 mile

(a)

(b)

Figure 10

Surface Water Rights (cf) for Scenarios 1A - 5B, 8 and 9

time period	node 3,6 (urban)	node 5,13 (urban)	node 3,10 (agric.)	node 8,16 (agric.)
1	5000	6000	20000	18000
2	5000	6000	7000	3000
3	5000	4000	18000	15000
4	5000	4000	8000	3200
5	3000	7000	22000	18000
6	3000	7000	8900	4000
7	7000	9000	21000	19000
8	7000	9000	9000	3800
9	6500	9000	21000	19100
10	6500	9000	8600	4100
11	7100	8500	1900	19800
12	7100	8500	8700	3800
13	7100	8500	19000	19800
14	7100	8500	9000	3800
15	8000	8900	18900	19700
16	8000	8900	8900	3700
17	8200	900	19100	20000
18	8200	900	9100	4000
19	8200	9100	20500	19900
20	8200	9100	8500	3900

Table 2a

5.2 INFLOW AND OUTFLOW

Figure 11 shows the schedule of surface water inflow over time designated for the simulations in this study. The inflows are distributed bimodally, with inflow in the first half of every year always exceeding that in the second half of the year. This trend is consistent with the high volume stream flows associated with spring snowmelt in mountains draining into watersheds in the west. The inflow pattern has a prominent maximum in the first half of year three, and minimum first and second season flows occurring in the fifth year. Two patterns of surface water outflow requirements are illustrated in this figure. The required outflow may symbolize a mandatory instream flow requirement for the protection of riparian habitat, for example, or the obligation of one state or management

Surface Water Rights (cf) for Scenarios 6 and 7

time period	node 3,6 (urban)	node 5,13 (urban)	node 3,10 (agric.)	node 8,16 (agric.)
1	8500	9300	22000	18700
2	8500	9300	8600	3700
3	8600	9200	23000	19000
4	8600	9200	7900	4000
5	8650	9300	23500	19500
6	8650	9300	7500	4500
7	8750	9400	24000	20000
8	8750	9400	8000	4000
9	9000	9500	23900	221000
10	9000	9500	7900	4000
11	8900	9600	24000	20500
12	8900	9600	8000	35000
13	8900	9500	24000	21000
14	8900	9500	7900	4000
15	9000	10000	23000	19000
16	9000	10000	8800	5000
17	9100	10800	24100	20800
18	9100	10800	8100	4800
19	9500	11000	25000	22000
20	9500	11000	8700	4000

Table 2b

district to deliver a particular volume of surface water to a downstream counterpart. The two different outflow requirements illustrated in Figure 11 are incorporated into the simulations in this study in order to test the performance of each management system under increased surface water delivery obligations. Scenarios 6 and 7 have slightly higher surface water outflow requirements and larger surface water rights than in the other scenarios, thus placing an increased

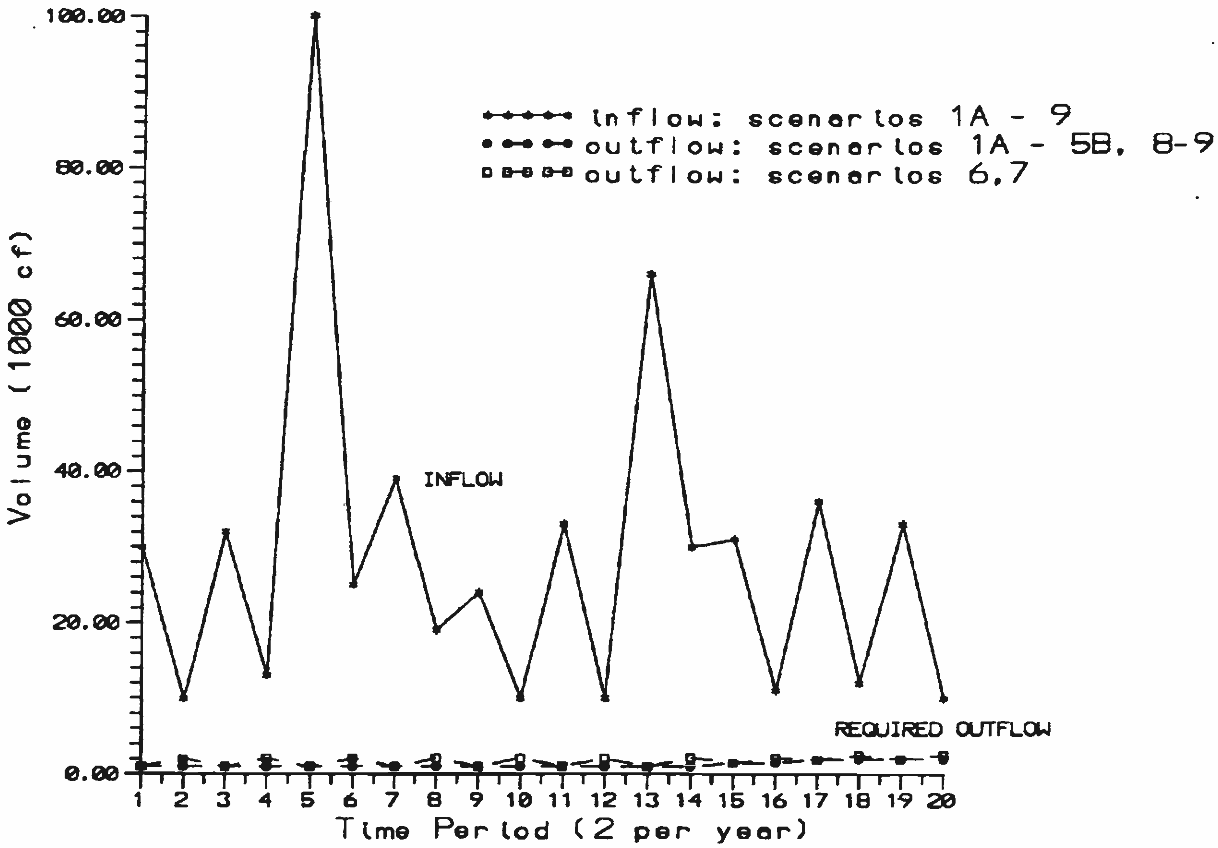


Figure 11

Surface Water Inflow and Required Outflow for Each Time Period

5.3 EXPECTATIONS

Based on the model structures and the variables described in Tables 1a and b, certain results may be anticipated.

5.3.1 Pumping Rates

In general, the form of Equation 16 suggests that a larger negative α (more elastic demand) would yield a lower pumping rate, for all other variables held constant.

Thus, in simulations where $\alpha_{agric} = -1.0$ and $\alpha_{urban} = -0.5$ (SSIM and OSIM scenarios 2A, 2B, 5A, and 5B), agricultural wells would pump less than otherwise equivalent urban wells. Similarly, higher groundwater costs yield lower pumping values. This result suggests that, in cases where the water table approaches critical levels in SSIM and OSIM, pumping rates will decrease, whereas no such effect would appear in the GSIM simulations.

5.3.2 Drawdowns

Of course, drawdowns depend on pumping rates, but some generalizations may apply. The augmentation well in the GSIM model should greatly reduce the need for individual diverters to pump from their private wells. Thus, drawdowns at diversion points should be lower in GSIM than in SSIM and OSIM, but potentially large drawdowns at the augmentation well node might occur in GSIM, while no such effect will be seen in SSIM/OSIM.

GSIM places no restriction on drawdowns, either directly or through price incentives, so drawdowns may progress more readily below the same level as the critical head elevation in the SSIM/OSIM models. Because GSIM depends solely on non-irrigation season recharge for recovery of groundwater levels, while SSIM and OSIM recharge directly into wells during all time periods when the availability of surface water permits, drawdowns in some nodes should be higher for GSIM than for SSIM/OSIM simulations. In the long term, if recharge fails to keep pace with groundwater production, unrestricted drawdowns in GSIM could lead to subsidence problems or excessive capture of streamflow to the point that the replacement water supply wells could no longer compensate for damage done to senior water rights holders. On the other hand, the high lift costs associated with very large drawdowns could eventually result in voluntary cut-backs in groundwater production.

The hydrogeologic environment may have a significant impact on the relative success of each management system. For example, the hypothetical basin in this study has a constant-head boundary at the north-west end. This "infinite" source of capture may permit the systems to reach a quasi-steady-state after water ceases to come from aquifer storage, and only drawn from this boundary. Under a head-dependent boundary, for example, capture would depend on the gradient between head levels in the basin of interest as well as in the adjacent basin. Thus if groundwater levels declined in the adjoining basin, the head gradient might actually draw water out of the simulation area instead of providing a source of recharge or capture for the users there.

The effect of varying transmissivity distributions should be smaller drawdowns in cases where the transmissivity of the aquifer at a well is increased (see Figure 10). Also, the extent of aquifer layering, and the relative thicknesses of each layer could have considerable impacts on the behavior of drawdowns under the three management systems as vertical head gradients develop.

5.3.3 Diversions

GSIM's prior appropriation system dictates that some users will lose their surface water diversions before others when surface water supplies fall short of demands. The administrative allocation basis for the SSIM/OSIM models requires that all users of a certain class (agricultural or urban) share the burden of a shortage in surface water supplies, so that, ideally, all users in a group may continue to divert part of their surface water entitlements before any one user loses his entire surface water diversion. The management rules in SSIM and OSIM prescribe a particular method for reducing diversions to agricultural users first, then urban users, but the reductions are not directly tied to the amount of available surface water in the current time period (see above discussion under "SSIM and OSIM Models in Detail"). Thus, even though the agricultural users in the system may experience some restriction on their diversions, it is still possible for the urban users to lose all or part of their diversions while the agricultural users still divert water. Consequently, the proportion of groundwater to surface water required for different classes of users in SSIM and OSIM depends heavily on the total surface water availability in the system (at the present and in the recent past). In GSIM, however, senior users will generally satisfy less of their total demand for water from groundwater than will more junior users because of the economic savings incurred from diverting instead of pumping.

Chapter 6
Results

The graphs in Appendices A through E illustrate the results of the twelve simulations described in the previous section. The plots fall into four categories: **drawdown**, **river leakance capture**, **diversions**, and **pumping**. Each category of graphs gives detailed information about the relative performance of each type of management system under consideration, but the combined set of graphs reveals more about the general behavior of each system relative to the other two. This section of the report first evaluates and discusses the information provided in each category of graphs, and the following section consolidates the category results into a set of general conclusions about the management models.

Notation: references such as "well 1,2,3" for example, imply the well pumping from layer 1 in the node at row 2, column 3 of the model grid area. "Node 2,2,2" simply means aquifer layer 2, row 2, column 2. Node designations with only two characters (i.e., "3,2") refer to that row and column in the surface layer (1).

6.1 DIVERSION PLOTS (Appendix A)

The most immediate result of each management system's operation is the delivery of a particular volume of water to each surface water right holder (diverter). In some cases, the system achieves its goal of satisfying all of the surface water demands, but in many cases, surface water shortages force the system to reduce or eliminate such deliveries to selected users. The way in which a conjunctive management system determines which users will be shorted and by how much distinguishes it from other types of systems. This contrast is especially vivid between the administrative allocation system (correlative rights doctrine) (California) and the prior appropriation doctrine (Colorado) management systems. Figures A1 through A12 show the volume of water delivered to each diverter under the three models GSIM, SSIM, and OSIM. The user's surface water right for the time period (time periods are numbered consecutively 1 through 20 for 10 years with 2 time periods each) is marked by a short-dashed line with a cross symbol at each time period. Diversions for the first time period in every year (odd numbered time periods on the plots) are connected by solid lines, while those for the second time period in each year (even numbered time periods on the plots) are linked by dashed lines.

In general, the GSIM model out-performed both SSIM and OSIM in successfully meeting the surface water needs of the users. Although the arrangement of the GSIM users in priority and in magnitude of surface water rights played a role in determining how well the system met the demands of each user, the presence of a supplemental water supply well upstream from the diverters (node 2,2,1) contributed to GSIM's ability to meet the surface water demands of its users. Although the results of this group of simulations indicates fewer shortages to GSIM diverters, one must note that the augmentation well is located adjacent to a constant-head boundary in the hypothetical basin. Thus, an endless supply of water may be captured across this boundary in order to supply downstream users. As suggested in the "Expectations" section above, alternative boundary conditions might provide very different results in terms of capture across this boundary area.

For all of the diverters, the plots for scenarios 1A, 1B, 2A, 2B, 4A, 4B, 5A, and 5B are identical except for the absence of diversions in the even numbered time periods in scenarios 4A - 5B. This result simply illustrates that the amount of water delivered to a user depends solely on the amount of surface water available and the user's water right, and is independent of the price elasticity of demand (α) or the transmissivity of the aquifer. Deliveries for scenarios 6 and 7 (Figures A3, A6, A9, and A12) are identical as well, but the extent to which surface water demands were met declined compared to all of the other scenarios as a result of larger surface water rights and increased surface water outflow requirements in these scenarios.

Well 1,8,16 (an agricultural diverter in all three systems) provides an interesting example for discussion. In scenarios 1A-5B (Figures A4 through A5), GSIM failed to meet the surface water demands of this user in time periods 9, 15, 16, 18, 19, and 20 by a respective 46%, 14%, 12%, 17%, 11%, and 58% in each case. In contrast, SSIM failed to meet the surface water demands of this diverter in every time period *except* 5, 6, 13, and 14. In most of the cases where GSIM's delivery fell short of the demand, it still delivered more than SSIM or OSIM. In two time periods, however, 9 and 20, both SSIM and OSIM delivered more water to the user than GSIM. The results for simulations 6 and 7 display this unusual behavior in even more time periods: 1, 2, 3, 9, 10, 11, 12, 16, 17, 18, 19, and 20. Interestingly, the years in which GSIM met the surface water demand for this user correspond to years of high surface water inflows (time periods 5-6 correspond to year 3, 7-8 to year 4, and 13-14 to year 7). No such correlation appears in the SSIM and OSIM results. In fact, a very different trend in these two models (*decreased* deliveries in "wet" years, *increased* deliveries in "dry" years) reflects the significance of the *history* of inflows and deliveries in these systems' decision processes (see explanation of surface water distribution process under section entitled "OSIM and SSIM Models in Detail"). The rule sets for these model systems incorporate previous years' deliveries, as well as the change from last year's to the current year's inflow, in the formula for calculating deliveries in the current year (during a shortage). Under conditions where a slight shortfall exists, for example, even though the current year is *wetter* than the previous one, the percentage by which deliveries to users are cut is large because the formula calculates the absolute value of (last year's inflow − this year's inflow) ÷ last year's inflow. This is probably an unintended result for a formula that was intended to compensate for shortages during dry years following wet years.

Figure A6c illustrates the importance of the spatial arrangement and seniority of diverters in the GSIM model. This graph plots the volumetric diversions for the agricultural user at row 8, column 16 (written as node 8,16) for three different seniority arrangements among the four diverters in the model configuration. The priority (from most senior to most junior) of the users in the three cases can be summarized as follows:

(reproduced from Table 1b)

	G1A	G1C	G1D
(row,col.)	3,6	5,13	8,16
	5,13	8,16	3,6
	3,10	3,6	3,10
	8,16	3,10	5,13

As shown in Figure A6c, the G1A configuration is the only scenario of the three listed above in which the user at node 8,16 does not receive his desired surface water allotment. This result is reasonable in light of the fact that the node 8,16 diverter has 4th priority in G1A, 3rd priority in G1C, and 1st priority in G1D. As the user with lowest priority in G1A, this diverter should be the first to suffer a diminished diversion in the event of a surface water shortage. The same type of result occurs for the diverter at node 5,13 in scenario GD1 (see Figure A12c). While this diverter benefited from having 2nd and 1st priority in scenarios G1A and G1C, respectively, his standing as most junior (4th priority) in the G1D case resulted in reduced surface water deliveries in six time periods (9,15,16,18,19, and 20).

The only configuration under which the diverter at node 3,10 was *not* shorted in one or more time periods was G1A, where he had 3rd priority (Figure A3c). Although this user also had 3rd priority under the G1D arrangement, the specific combination of seniorities and magnitudes of water rights of all of the users together resulted in reduced diversions to that node (3,10) in the G1D simulation. The user at node 3,6 suffered no shortages in any of the three scenarios, even though his priority dropped to 3rd in the G1C case.

In all cases, SSIM delivered as much or slightly more water to each diverter than OSIM. In general, both models were equally successful at delivering the full volume of each diverter's water right. In times of shortage, however, OSIM's mandatory recharge policy reduced the amount of water available for delivery to diverters, thus causing its performance to be slightly worse than SSIM's in terms of the volume of water delivered to each user (see Figure A7 for diversion node 3,6 as an example).

6.2 PUMPING PLOTS (Appendix B)

Appendix B contains graphs of pumping rates vs. time for the pumping wells in the model area. For the purposes of plotting, scenarios 8 and 9 were ommitted because of their redundancy with scenarios 1A and 1B. The only purpose of these two additional simulations is to demonstrate the effect on drawdowns of removing the independent pumping wells. Therefore, the drawdown plots (discussed in the following section) will be the only graphic presentation of these two scenarios.

The most outstanding trend visible in the plots of pumping rates over time for the agricultural wells at nodes 1,3,10 and 1,8,16 (Figures B1 through B6) is that the SSIM model wells consistently pump at higher rates than those in the OSIM model, and OSIM wells pump more than those in GSIM. Figure B1 illustrates this trend for the well in layer 1 row 3, column 10 (node 1,3,10). As with well 1,8,16, scenarios 1A, 1B, 4A, and 4B ($\alpha_{agric} = -0.5$) result in much higher pumping rates than those in scenarios 2A, 2B, 5A, and 5B ($\alpha_{agric.} = -1.0$), respectively, because of the more negative elasticity of demand in the second group of scenarios. At first, the discrepancy between the pumping rates of the SSIM and OSIM models appears unexpected because the two model systems operate under the same general rules for distributing surface water supplies to users. Given that the surface water users in OSIM actually receive slightly *less* water than the corresponding users in the SSIM model, one would expect the OSIM wells to pump slightly *more* water than those in SSIM. The observed trend is just the opposite, however, and can be explained by a lower ground-water cost for agricultural users in SSIM than in OSIM. The SSIM model prices agricultural-use groundwater at 1/4 the price for urban-use groundwater, while the OSIM system charges 1/2 as much for agricultural-use as for urban-use groundwater. Thus, the higher cost results in a smaller demand (see Equation 16) and lower pumping rates in the OSIM simulations. GSIM pumps at an even lower rate than either OSIM or SSIM (roughly half the SSIM rate) because no discount is made for any type of groundwater use. In other words, the price of groundwater listed in the price table (input for program) applies to all groundwater users in GSIM.

The second obvious characteristic of the plots for the two agricultural diversion nodes (1,3,10 and 1,8,16) is the decrease in pumping rates from the odd numbered time periods (first half of each year) to the even numbered time periods (second half of each year). This pattern emerges from the significantly lower surface water rights assigned to the agricultural diverters in the second half of each year (to reflect reduced consumption in winter vs. summer) compared to the first (see Tables 2a and b)), and the resultant calibration constants derived from Equation 16. For the urban diversion node wells (nodes 2,3,6 and 2,5,13), no such distinction exists because the surface water rights for these users remain relatively constant for both time periods in each year.

The identical pumping rate plots for scenarios 1A (transmissivity distribution 1 [T1] in all A scenarios, T2 in all B scenarios) and 1B, 2A and 2B, 4A and 4B, and 5A and 5B (except for zero pumping in even numbered time periods in 4A-5B) show that pumping in these wells is essentially insensitive to the transmissivity changes indicated in Figure 10. The fact that pumping rates are independent of the previous time periods' pumping rates explains why plots 1A and 4A, 1B and 4B, 2A and 5A, and 2B and 5B are identical in the odd-numbered time periods. No pumping occurs in scenarios 4A-5B because the surface water rights in these cases are set to 0.0, thereby producing zero calibration constants for the demand calculations in those time periods. These simulations (with zero water rights in the second half of each year) were designed to permit a comparison of the OSIM and SSIM systems to the GSIM system under a condition which would permit significant recharge in GSIM. Off-season (non-irrigation season) natural recharge which is so important to GASP is simulated in GSIM with artificial recharge of surface water into pumping wells in a manner analogous to that described for the OSIM and SSIM models when a surface water surplus occurs. For a reasonable comparison to zero off-season diversions in GSIM, water rights for the four corresponding diverters in SSIM and OSIM were also set to zero in the second half of each year in simulations 4A-5B.

The peak pumping rates occur during time periods 5,8,9 and 19 for the layer 1 well at node 3,10 in scenarios 1A-5B. For the same well, scenarios 6 and 7 produced peak pumping rates in time periods 9,16,19, and 20. The peak in time period 5 follows a strong dip in the pumping rates in time period 3. This behavior illustrates the important effect of the lift (energy) cost associated with pumping water from the water table to the ground surface. Since time period 5 exhibits the highest surface water inflow in the entire 20 time period simulation (see Figure 11), and since all of the model systems successfully meet surface water demands in this time period, one would expect pumping rates to decline from their prior levels. The sharp decline in pumping rates in time period 3 followed by a sharp increase in time period 5 is primarily a function of fluctuating lift costs. While the cost per volume of groundwater increased from time period 1 to time period 5, the lift costs increased from time period 1 to time period 3, then decreased to their original levels in time period 5, producing a higher demand for groundwater and thus, higher pumping rates in that time period.

Similar explanations exist for the other peaks and dips displayed in the pumping rate plots. For example, the peak in time period 9 coincides with the lowest inflow for the first time period in any year in the simulation. The diversion plots (discussed above) show many shortfalls in surface water deliveries for this time period, and the consequence of increased groundwater pumping is entirely reasonable according to Equation 16. Time period 10, however, not only followed an extremely low inflow, but its inflow was the lowest of the entire simulation. Pumping rates generally dropped in this time period, though, due to a sharp increase in lift costs from time period 9 to 10.

The difference in peak pumping rates in scenarios 6 and 7 from all of the other scenarios comes from the combined effects of increased surface water stresses on the system, as demonstrated in the diversion plots discussed in the previous section. Like the contrast between scenarios 1A and 1B, pumping rates drop dramatically (roughly a factor of four) from scenario 6 to scenario 7 because of the change in $\alpha_{agric.}$ from -0.5 to -1.0.

A comparison of pumping rates in well 1,3,10 for the three GSIM scenarios (Figure B3c) shows very little distinction between the pumping rates for the three scenarios. The largest contrast appears in time period 9, where the G1C scenario produces a slightly higher pumping rate than G1D, and the G1D rate slightly exceeds the G1A rate. This trend is consistent with the record of surface water deliveries to this user illustrated in Figure A3c, and discussed earlier. In scenario G1D, the diverter at node 3,10 held 4th priority (see Table 1b), and surface water deliveries to that node were curtailed in time period 9 for that scenario. While this user held 3rd priority in scenarios G1A and G1C, his surface water delivery for time period 9 and scenario GA1 slightly exceeded that for the same time period in scenario G1C.

The pumping rates for the GSIM scenarios G1A, G1C, and G1D for the layer 1 well at node 8,16 fall into a different order, again reflecting the seniority of the user in each case. The pumping rates in time period 9 were equal for scenarios G1C and G1D, where this user held 2nd and 1st priority, respectively. The rate of pumping for the same well under the G1A scenario exceeded that for the other two scenarios, as would be expected for a drop in surface water priority to 4th place.

Patterns of pumping rates shown in Figures B7 through B12 for the wells at the nodes 2,3,6 and 2,5,13 (urban users in OSIM/SSIM) display somewhat different characteristics than those for the other two wells described above. First, the pumping rates remain fairly constant from the first half of the year (odd numbered time periods) to the second half of the year (even numbered time periods) in each year because of the relatively constant surface water rights over those times (see Tables 2a and b). Second, the GSIM pumping rates depart significantly from the OSIM and SSIM rates for scenarios where α_{urban} is distinguished from(scenarios 2A, 2B, 5A, 5B, and 7). The reason for the departure (a significant decrease) is that GSIM does not distinguish between agricultural and urban diverters, so the $\alpha_{agric.}$ value applies to all pumpers. Thus, for the four scenarios where $\alpha_{agric.} = -1.0$ and $\alpha_{urban} = -0.5$, Equation 16 dictates that GSIM pumpers will have smaller demands and will subsequently pump at lower rates than corresponding urban users in OSIM and SSIM.

For the scenarios where $\alpha_{agric.} = \alpha_{urban} = -0.5$ (scenarios 1A, 1B, 4A, 4B, 6, 7), the OSIM pumping rates very slightly exceed the SSIM rates (a reflection of the mandatory recharge policy in the OSIM model), but the distinction is virtually invisible on the plots. The GSIM pumping rates for these scenarios at wells 2,3,6 and 2,5,13 are either equal to or lower (usually by less than a factor of two) than those for OSIM and SSIM. GSIM's better success at meeting the surface water demands of its users supports this result.

In all other respects, the trends described for the agricultural diversion point wells (nodes 1,3,10 and 1,8,16) also apply to the two urban wells (2,3,6 and 2,5,13). Because they did not affect his surface water diversions, the different priorities of the diverter at node 3,6 in scenarios G1A, G1C and G1D had no impact on the pumping rates at that well (see Figure B9c).

The GSIM scenarios G1A, G1C and G1D illustrated in Figure B12c for well 2,5,13 show higher pumping rates in the G1D scenario for time periods 9, 15, 19 and 20 than in the other two scenarios. Again, the low (4th) priority of this user in the G1D scenario (see Table 1b) led to increased pumping at that node for the time periods where surface water deliveries were reduced in order to meet the needs of more senior users. The 5,13 user had 2nd priority in the G1A scenario and 1st priority in G1C, and he incurred no surface water reductions in those simulations.

Figures B19 through B21 show pumping rates for the replacement water supply well in the GSIM model system (node 2,2,1). (This well was not present in OSIM and SSIM.) A quick inspection of the plots reveals identical graphs for scenarios 1A-5B and for scenarios 6 and 7. Unlike other pumping wells in the system, well 2,2,1 operates strictly in response to diversions (i.e., whether or not supplemental water is required by diverters), not to price. GASP membership fees pay for the operation of its "replacement water supply wells," and, consequently, those wells operate in a manner completely different from privately owned wells.

For scenarios 1A-5B, the well pumped at a non-zero rate for all time periods except 5 and 6 (year 3) and 13 and 14 (year 7). Figure 11 shows that these four time periods had the highest inflows of the simulation, and the diversion plots (Appendix A) for the GSIM wells indicate that all surface water demands were met during these time periods. For most of the simulation, however, this well actively supplemented the surface water supply for the GSIM diverters. In fact, the well pumped at its maximum capacity (set to .001 cfs for the purposes of illustration) in 6 out of 20 time periods in scenarios 1A - 5B, and in 13 of 20 time periods for scenarios 6 and 7. Even though its capacity was kept low in these simulations, this well obviously plays an important role in meeting the needs of the GSIM users.

The "independent well" (non-surface water user) at node 1,7,5 plays a very interesting part in the overall results of simulations 1A - 7. This well presents the only case where the hydraulic head in the aquifer dropped below the critical head elevation designated for that point in the SSIM and OSIM systems. As a price incentive to reduce drawdowns, these models triple the volumetric price of groundwater when the aquifer head reaches a certain minimum level (specified by the program user). For SSIM, this level is specified as a *threshold* value; a small increment above the critical head elevation for each node. Once the head in a well comes within this threshold value (one foot in these simulations) of the critical elevation, the groundwater price is tripled as an incentive to curb pumping. If the head then falls below the critical head level at that node, however, SSIM "shuts down" (forcibly discontinues pumping for at least one time period) the well until the head level recovers to a point above the critical head elevation. In OSIM, the threshold concept does not apply, and no provision exists for the forceful shut down of a pumping well. Instead, this system simply implements the price hike (triple the regular price) when heads reach the critical elevation, and demand calculations for each pumper determine at what rate each well will continue to operate. Both systems effectively reduce pumping when heads approach the critical elevation specified for each node, and thereby curtail drawdowns.

Figures B13a, B13c, B14a and B14c illustrate cases of reduced pumping in well 1,7,5 for the SSIM and OSIM simulations 1A, 2A, 4A, and 5A. Before examining these pumping graphs in detail, one should have an idea of the physical state of the water table over the course of the simulation. Table 3a lists drawdowns (in feet) for well 1,7,5 in each time period for the OSIM and SSIM simulations 1A and 4A. Careful observation of the data reveals a cyclic pattern in the drawdowns for each of the four cases listed. Drawdowns in the SSIM simulations always recover dramatically after reaching or exceeding 10 feet (from time period 5 to time period 6, for example). This recovery simply results from shutting off the well when the head reaches the critical head elevation (10 feet below the initial head at this node in this case). Notice the slight recovery in time period 4, for instance, when heads fall within 1 foot (the specified threshold limit) of the critical head elevation, and the price of groundwater subsequently triples. The corresponding recoveries after heads fall more than 10 feet are less pronounced in the OSIM simulations. This result makes sense considering that the

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(selected scenarios for SSIM and OSIM)

	(a)				(b)			
time period	SSIM1A	SSIM4A	OSIM1A	OSIM4A	SSIM2A	SSIM5A	OSIM2A	OSIM5A
1	7.107	7.107	7.106	7.106	7.100	7.100	7.099	7.099
2	8.652	8.645	8.695	8.688	8.459	8.454	8.546	8.541
3	9.798	9.791	9.805	9.799	9.738	9.734	9.757	9.752
4	8.989	8.976	10.38	10.37	7.772	7.762	10.21	10.20
5	10.69	10.670	9.020	9.009	10.33	10.32	7.562	7.555
6	4.919	4.901	10.82	10.80	4.721	4.710	10.24	10.23
7	10.27	10.25	9 .493	9.479	9.855	9.845	7.836	7.827
8	4.966	4.942	11.13	11.11	8.132	8.116	10.31	10.30
9	10.47	10.45	9.747	9.728	10.74	10.73	7.942	7.930
10	5.089	5.061	11.28	11.25	5.166	5.147	10.26	10.25
11	10.24	10.22	9.842	9.820	9.778	9.762	7.898	7.883
12	5.112	5.082	11.53	11.50	8.344	8.324	10.53	10.51
13	10.28	10.25	9.987	9.963	10.31	10.29	8.000	7.984
14	5.120	5.088	11.41	11.38	5.160	5.138	10.17	10.15
15	10.07	10.04	9.860	9.835	9.411	9.393	7.734	7.718
16	5.070	5.037	11.30	11.27	7.907	7.884	9.904	9.882
17	9.905	9.876	9.804	9.777	9.537	9.518	10.02	9.998
18	9.372	9.337	11.19	11.16	7.882	7.858	7.657	10.06
19	9.423	9.394	9.765	9.737	9.503	9.483	9.654	7.671
20	9.431	9.396	11.07	11.04	7.781	7.757	9.768	9.521

Table 3

only mechanism by which OSIM restricts pumping is through price incentives. Every time the drawdown in well 1,7,5 exceeds 10.0 feet, drawdowns in the following time period are somewhat lower, but the recovery is limited because the well continues to pump, but at a lower rate. The threshold concept does not apply to OSIM, so no change in drawdown trends occur until after the critical head level is breached.

The drawdowns for SSIM and OSIM simulations of scenario 4A are consistently (albeit slightly) smaller than those in the 1A simulations. This small difference reflects the change in pumping behavior of the surface water users from one scenario to the other. In 1A, surface water users have demands for water in both time periods of each year, but in 4A, demands in the second time period of each year are set to 0.0. Thus, the lack of pumping (even at very low rates) by the relatively distant surface water users translates to reduced drawdowns in well 1,7,5 for the 4A simulations.

The large contrast between plots for pumping rates in scenarios 1A, 2A, 4A, 5A and scenarios 1B, 2B, 4B, and 5B (Figures B13 and B14, for example) reflects the impact of different transmissivity distributions in the two groups (refer to Table 1a and Figures 10). In the 'A' scenarios, transmissivity distribution 1 produces drawdowns which breach the critical head level (10 ft.) specified in OSIM and SSIM. The same rule sets imposed on a system with transmissivity distribution 2, however, produce considerably smaller drawdowns in the 'B' scenarios, and the radical consequences of breaching the critical head level at well 1,7,5 seen in the 'A' scenarios never arise.

With that background, the pumping plots for well 1,7,5 become somewhat easier to interpret. In order to simplify the discussion, the following paragraphs will consider the SSIM simulations alone first, then move on to the OSIM and GSIM simulation results.

6.2.1 SSIM- 1,7,5 Pumping

The most obvious feature of Figure B13a (scenario 1A) is the drop (to 0.0 cfs) in pumping in time period 6 when the critical head level is first breached, and the sharp resumption of pumping after time period 16. Remembering that the dashed lines connect points for the second half of each year (not consecutive time periods), it is clear that well 1,7,5 is entirely shut down for the second half of six consecutive years (years 3-8) in the SSIM simulation. The solid line connecting the SSIM pumping rate values for the first half of each year (odd-numbered time periods) remain fairly level, indicating a relatively stable pumping rate in those time periods throughout the simulation. Table 3a supports the trends: drawdown in SSIM scenario 1A first exceeds 10.0 feet in time period 5, triggering the shut down of the well in the next time period. Drawdown recovers to 4.919 feet in the following time period, turning the well back on in time period 7. This renewed pumping, in turn, brings drawdown back to 10.27 feet, causing another shut down, and so on. The low, but non-zero, pumping rates displayed for SSIM in time periods 5, 18, 19, and 20 reflect drawdowns in the *threshold* range of between 9 and 10 feet where groundwater costs increase.

The only distinction between scenarios 1A and 4A is that surface water users have non-zero water rights in all time periods in 1A, and zero water rights in the second time period of each year in scenario 4A. Although the low pumping rates of the surface water users' wells do have a slight effect on drawdowns in the independent wells (nodes 1,7,5 and 2,10,8), Figures B14a and B15a show that the diverters' pumping does not influence the pumping activity of well 1,7,5 for scenarios 1A and 4A.

Figure B13c illustrates the consequence of applying a more elastic (-1.0 vs. -0.5) demand in the pumping rate calculations for well 1,7,5. The effect of this action is a lower demand by the user at node 1,7,5 and thus, lower pumping rates over the course of the simulation. The contrast between pumping rates is especially striking when drawdowns fall into the *threshold range* and groundwater prices triple (see Figures B13a and c, time period 5, for example). These lower pumping rates produce smaller drawdowns compared to those in scenario 1A, and the result is significant. Well 1,7,5 suffers shut downs in only 3 time periods (6, 10, and 14) in scenario 2A compared to 6 periods of shut down in scenario 1A. Reference to Table 3 confirms that in three time periods (7, 11, and 15), drawdowns for scenario 1A exceeded 10.00 feet, while those for scenario 2A remained less than 10.00 feet. Thus, when the critical head was breached in one case (1A), it was not in the other (2A) and pumping continued. Even though the well operated in all but 3 time periods in scenario 2A, it pumped at a reduced rate for many time periods as a result of drawdowns reaching the threshold level above the critical head elevation.

Scenarios 2A and 5A are direct analogs to 1A and 4A, but with $\alpha_{agric} = -1.0$ instead of -0.5. Like the plots for scenarios 1A and 4A, those for 2A and 5A (Figures B13c and B14c) show identical pumping patterns for SSIM throughout the simulation. Table 3a reveals the parallel changes in drawdowns between SSIM scenarios 2A and 5A which produce identical corresponding pumping patterns for the two cases.

Scenarios 1B, 2B, 4B, and 5B (Figures B13b, B13d, B14b and B14d) provide a beautiful example of the sensitivity of pumping rates at this node to <u>transmissivity</u>. The 9-fold increase in transmissivity at node 1,7,5, (see Figure 10) in addition to the effects of transmissivity changes at other nodes in the aquifer, from the A scenarios to the B scenarios diminished drawdowns enough to prevent any breaching of the critical head elevation in all of the B scenarios. As a result, pumping rates remained fairly constant, decreasing slightly over time. This slight decreasing trend reflects gradual increases over the course of the simulation in the cost of groundwater and the energy cost associated with lifting the water from the water table to the ground surface. Small upward inflections in pumping rates in time periods 9 and 12 reflect short-term price decreases.

Table 4 lists drawdowns for SSIM and OSIM scenarios 1A and 6 as well as 2A and 7. Pumping rates for scenarios 6 and 7 are plotted in Figures B15a and b, respectively. Scenarios 6 and 7 are identical to their counterparts 1A and 2A except for <u>larger surface water rights</u> for diverters and <u>higher streamflow exit requirements</u>. Higher water demands on the system result in higher pumping rates in wells at diversion nodes, and subsequently higher drawdowns across the model area. Table 4a reveals that the first critical difference in drawdowns between SSIM scenarios 1A and 6 occurs in time period 4. The small discrepancy (0.014 ft.) in drawdowns for the two scenarios has important ramifications for the pumping behavior of well 1,7,5. In time period 4, drawdown slightly exceeds 9.0 feet in scenario 6, while it remains just under 9.0 feet in scenario 1A. The 9.0 foot level is one foot (the specified threshold) above the critical head elevation (10 ft. below initial steady-state head) at that node. Thus, for drawdowns between 9.0 and 10.0 feet, the high price of groundwater reduces demand, and hence, pumping rates, at that node. In the case of well 1,7,5, a lower time period 5 pumping rate in scenario 6 compared to 1A results in a smaller drawdown for that scenario. When drawdown exceeds 10.0 feet in time period 5 for scenario 1A, the well shuts off, but a drawdown of only 9.232 feet in time period 5 for scenario 6 allows the well to continue pumping in the next time period (see Figures B13a and B15a). In time period 6, continued pumping in scenario 6 produces 9.418 feet of drawdown, while drawdown for scenario 1A rebounds to 4.919 feet after discontinued pumping in that time period. The shaded areas in the first two columns of Table 4a mark the time periods where drawdowns exceed 10.00 feet in one scenario (SSIM 1A or 6) but not in the other. Figure B15a shows that, in stark contrast to scenario 1A, well 1,7,5 never shuts down in the second half of any year, but it is completely shut down for the first half of each year beginning in year 7 (time period 13). For 9 out of the 20 time periods, SSIM pumping rates for well 1,7,5 in scenario 6 maintain a reduced, but non-zero level. These time periods are those in which drawdowns fell between 9.0 and 10.0 feet (see Table 4a).

Inspection of Figures B13c and B15b indicates identical pumping rates for SSIM scenarios 2A and 7 in well 1,7,5. The first two columns in Table 4b list drawdowns for these two scenarios. Although drawdowns for scenario 7 slightly exceed those for scenario 2A (as would be expected for higher surface water demands), the patterns of drawdown fluctuations are roughly parallel, with no cases of one scenario's drawdowns breaching the threshold or critical head level when the other does not. Interestingly, the important difference between scenarios 6 and 7 came in time period 4. In time period 3, drawdowns in for both scenarios (6 and 7) exceeded 9.0 feet, triggering a price increase in groundwater and reduced pumping. Because of the more elastic demand in scenario 7 ($\alpha_{agric} = -1.0$ vs. -0.5), pumping drops to a lower level in scenario 7 compared to 6 (see Figures B15a and b). Thus, drawdowns rebound to a higher level (7.783 ft.) in scenario 7 than in scenario 6 (9.003 ft.), and the cycles of pumping in these two scenarios diverge for the remainder of the simulation.

6.2.2 OSIM - 1,7,5 Pumping

While OSIM and SSIM have the same rules of surface water distribution, differences in <u>groundwater pricing rules</u> between the two systems produce very distinct pumping patterns in well 1,7,5. Figure B13a shows the well pumping at the same rate in both models for the first three time periods of scenario 1A, but diverging sharply

DRAWDOWN IN WELL 1,7,5

(selected scenarios for SSIM and OSIM)

	(a)				(b)			
time period	SSIM1A	SSIM6	OSIM1A	OSIM6	SSIM2A	SSIM7	OSIM2A	OSIM7
1	7.107	7.111	7.106	7.109	7.100	7.103	7.099	7.102
2	8.652	8.659	8.695	8.702	8.459	8.465	8.546	8.552
3	9.798	9.810	9.805	9.817	9.738	9.747	9.757	9.765
4	8.989	9.003	10.38	10.40	7.772	7.783	10.21	10.22
5	10.69	9.232	9.020	9.036	10.33	10.34	7.562	7.575
6	4.919	9.418	10.82	10.84	4.721	4.735	10.24	10.25
7	10.27	9.637	9 .493	9.509	9.855	9.868	7.836	7.848
8	4.966	9.704	11.13	11.14	8.132	8.143	10.31	10.32
9	10.47	9.921	9.747	9.761	10.74	10.75	7.942	7.953
10	5.089	9.886	11.28	11.29	5.166	5.176	10.26	10.27
11	10.24	9.948	9.842	9.855	9.778	9.788	7.898	7.907
12	5.112	10.08	11.53	11.54	8.344	8.354	10.53	10.54
13	10.28	5.498	9.987	10.00	10.31	10.32	8.000	8.009
14	5.120	10.45	11.41	11.42	5.160	5.169	10.17	10.18
15	10.07	5.339	9.860	9.872	9.411	9.149	7.734	7.742
16	5.070	10.25	11.30	11.32	7.907	7.915	9.904	9.911
17	9.905	5.212	9.804	9.816	9.537	9.545	10.02	10.02
18	9.372	10.02	11.19	11.20	7.882	7.890	7.657	7.664
19	9.423	5.105	9.765	9.777	9.503	9.511	9.654	9.662
20	9.431	9.813	11.07	11.08	7.781	7.790	9.768	9.776

Table 4

after that time. Drawdowns for scenario 1A are listed for SSIM and OSIM in Table 3a. SSIM experienced it first sharp decrease in pumping in time period 4, but OSIM's first sharp drop in pumping came in time period 5. OSIM does not shut down pumping wells when drawdown exceeds the critical head limit, but increased groundwater costs reduce pumping rates and permit a small degree of recovery in head levels. As seen in Figure B13a, OSIM pumping rates remain at a reduced, but non-zero, level for the first half of every year after year 2. These low pumping rates produce just enough recovery in heads to permit a return to higher rates of pumping in the second half of each year. Thus, while the trend was just the opposite in SSIM scenario 1A, OSIM pumping is higher in even-numbered time periods and lower in odd-numbered time periods.

Figures B13b ($\alpha_{agric.} = -0.5$) and B13d ($\alpha_{agric.} = -1.0$) show quite different pumping patterns for OSIM well 1,7,5 than those seen in Figures B13a and c. The transmissivity distribution 2 (see Figure 10b) used in these scenarios results in smaller drawdowns at node 1,7,5. These smaller drawdowns, in turn, insulate the well from any restrictions incurred by drawdowns approaching the critical head elevation, as seen in scenario 1A. Without such restrictions, OSIM and SSIM pump at roughly parallel rates, with OSIM pumping at a slightly lower rate than SSIM because of the higher cost of groundwater in that system. The difference in α_{agric} from scenario 1B to 2B (-0.5 to -1.0) has the general effect of reducing pumping rates in the second scenario.

Scenarios 2A and 5A produced similar pumping results for this well, with pumping patterns diverging only after time period 17. The more negative α_{agric} in these scenarios caused the pumping rate to drop to a lower level when the critical head level was breached than it had in scenarios 1A and 4A (see Equation 16 and Figures B13a and c). Mimicking the pattern of scenario 1A, the OSIM pumping rates in scenarios 2A and 5A drop significantly in time period 5 after drawdown first exceeds

10.00 feet in both cases (see Table 3b). Reduced pumping in the odd-numbered time periods produces enough recovery in heads to permit a return to higher pumping rates in the even-numbered time periods for both scenarios. In time period 17, however, drawdown in scenario 2A exceeds the critical head limit, while it does not in scenario 5A (see last two columns in Table 3b). Again, a very small discrepancy (.022 ft.) in drawdowns has a strong effect on pumping patterns. As shown in Figures B13c and B14c, pumping in scenario 2A drops significantly in time period 18, but it actually increases slightly in that time period for scenario 5A. This increased pumping, however, produces drawdown of more than 10.00 feet, and pumping subsequently declines in time period 19 (scenario 5A). The reduced pumping of scenario 2A (time period 18) allows the drawdown at node 1,7,5 to recover to 7.657 feet, and pumping to resume at a higher rate for the last two time periods (see Figure B13c).

Table 3a illustrates the parallel patterns of drawdown fluctuations in OSIM scenarios 1A and 4A. Even though surface water diverters do not pump in the second half of each year in scenario 4A, the resultant recovery in heads is so slight that it has no effect in the pumping behavior of well 1,7,5 (see Figures B13a and B14a). Similarly, plots for pumping rates in scenarios 4B and 5B (Figures B14b and d) are identical to those for scenarios 1B and 2B (Figures B13b and d).

Unlike the very distinct pumping patterns seen in SSIM scenarios 1A and 6, pumping patterns for OSIM scenarios 1A and 6 are identical. From Table 4a, it is clear that the larger surface water demands on the system in scenario 6 produce slightly larger drawdowns in that case compared to scenario 1A. The absence of a threshold criterion or any provision for shutting down wells in OSIM, however, permits drawdowns to reach significantly higher levels than in corresponding SSIM scenarios. Without the threshold criterion of the SSIM system, OSIM pumping rates are less sensitive to drawdowns in the 9.0 to 10.0 foot range. Consequently, pumping rates for scenarios 1A and 6 are the same, in spite of small variations in drawdowns. Note that in time period 13, OSIM scenario 6 produces a drawdown of exactly 10.00 feet. If this drawdown had *exceeded* 10.00 feet, even by .001 foot, the pumping rate for that well would have dropped, and the pattern of pumping would have been different for the remaining time periods of the simulation.

The same logic used to analyze OSIM scenario 6 applies to scenario 7. Scenario 7 pumping rates are identical to those in scenario 2a in spite of slightly higher drawdowns in scenario 7 (see Table 4b and Figures B13c and B15b).

6.2.3 GSIM - 1,7,5 Pumping

Because GSIM does not employ the critical head elevation concept to discourage excessive pumping, pumping rates remain relatively constant throughout the course of the simulations. The major controls over pumping rates in the GSIM simulations are the price of groundwater per unit volume and the energy (lift) cost for bringing groundwater to the surface. Groundwater charges are provided to the simulation programs in the form of a cost table for each time period.[63] This table includes volumetric water costs and energy costs for specified lifts. In the case of well 1,7,5, the initial lift of 30 feet (see PLIFT1 value in input file for GSIM 1A) means that price increases will occur at drawdowns of 2, 4, 6, 10, and 15 feet which correspond to the price table lifts of 32, 34, 36, 40, and 45 feet.

The initial pumping value for all three management models of 2.0 cfs is an artifact of the calibration of the demand curve for each well (see Equation 16). After

[63] Lacher and Maddock, 1992, Response Functions in the Comparison of Conjunctive Management Systems, Department of Hydrology and Water Resources publication (in progress), University of Arizona.

the first time period, pumping rates adjust to reflect the differences in the management schemes. Figures B13a and c show that pumping rates for GSIM scenarios 1A and 2A are much less volatile than those for the corresponding OSIM and SSIM scenarios. Scenarios 1A and 2A reflect the change in α_{agric} from -0.5 to -1.0. The pattern of pumping rate fluctuations remains the same, but the actual pumping rate values decrease from scenario 1A to 2A, and the fluctuations between time periods are larger in scenario 2A. The magnitude of change in pumping rate change from one time period to the next is strongly tied to the α_{agric} value, while the direction of change (higher or lower) depends on the price of groundwater and the lift cost for each time period.

For example, the price tables for each time period are identical in scenarios 1A and 2A. Plots of pumping rates for both scenarios (Figures B13a and c) show decreasing pumping rates from time period 7 to 8, then increasing from time period 8 to 9, and again decreasing in time period 10. Table 5a lists the groundwater prices given in the input files for these time periods, and Table 5b lists the drawdowns for the corresponding time periods in each scenario. The cost/unit volume of groundwater increases from time period 7 to time period 8, but then remains constant through time period 10. The lift costs, however, remain constant for time periods 7 and 8, decrease in time period 9, and increase in time period 10. The drawdowns listed in Table 5b for GSIM scenario 1A increase very slightly from time period 7 to 8, then increase more significantly in time period 9, and increase only minutely from time period 9 to 10. This pattern of change in drawdowns suggests that the decrease in lift costs in time period 9 played a big role in allowing drawdowns to increase, but the increase in lift costs in time period 10 played an equally strong part in holding drawdowns at their previous levels.

Other scenarios show similar responses to changes in groundwater charges. In scenarios 2A - 5B, where $\alpha_{agric} = -1.0$, drawdowns actually decreased in the in the face of higher lift costs during time period 10 (drawdown figures are discussed in detail in the following section). In most cases, drawdowns increased somewhat from time period 7 to 8 even though volumetric groundwater costs increased. For scenarios 2A, 5A, and 7, however, the high initial drawdowns and the large negative α_{agric} produced large enough drops in pumping rates to reduce drawdowns in time period 8.

Figure B14c shows a time period 8 pumping rate for GSIM of 1.60 cubic feet per second (cfs) for scenario 5A, while pumping for the same time period in scenario 2A is 1.532 cfs. Although Table 5b indicates that the two scenarios have the same 10.00 foot drawdown in the previous time period, the computer simulation program utilized more than four significant digits in the drawdown values used to calculate pumping rates. Thus, instead of giving identical pumping rates for these scenarios, the program reveals that drawdown in the 2A case actually exceeds 10.00 feet, thereby bumping the well into the next category on the groundwater price table (Table 5a), and lowering the demand of well 1,7,5. One could anticipate this result (larger drawdowns in 2A) by considering that scenarios 4A-5B include zero pumping rates for the four diverters as well as intentional recharge of surface water through one or more recharge wells. Again, the sensitivity of the computer simulation program to minute differences in heads has important implications for the operation of the various conjunctive management systems.

GSIM scenarios 6 and 7 produce pumping rates (see Figure B15a and b) identical to those in scenarios 1A and 2A, respectively. As shown in Table 5b, the increased surface water demands on the system in scenarios 6 and 7 do result in slightly higher drawdowns, but the increases are not substantial enough to effect a change in pumping patterns.

Table 5

	time pd. 7		time pd. 8		time pd. 9		time pd. 10	
Lift (ft.)	cost/ vol.	lift cost	cost/ vol.	lift cost	cost/ vol.	lift cost	cost/ vol.	lift cost
32	1.3	.65	1.4	.65	1.4	.60	1.4	.70
34	1.3	.75	1.4	.75	1.4	.70	1.4	.80
36	1.3	.85	1.4	.85	1.4	.80	1.4	.90
40	1.3	.95	1.4	.95	1.4	.90	1.4	1.00
45	1.3	1.05	1.5	1.05	1.4	1.00	1.4	1.10

(a) Groundwater Price Tables for Time Periods 7 - 10

Drawdown (ft.)				
Scenario	time pd. 7	time pd. 8	time pd. 9	time pd. 10
1A	10.72	10.79	11.00	11.01
1B	4.849	4.921	5.028	5.047
2A	10.00	9.706	10.10	9.778
2B	4.401	4.451	4.568	4.546
4A	10.70	10.77	10.98	10.98
4B	4.838	4.903	5.014	5.027
5A	10.00	9.918	10.14	9.791
5B	4.398	4.447	4.564	4.541
6	10.73	10.80	11.01	11.02
7	10.01	9.709	10.10	9.781

(b) Drawdowns in GSIM Well 1,7,5 for Time Periods 7 - 10

Figure B15c plots pumping rates for well 1,7,5 under the three different priority arrangements in GSIM scenarios 1A, 1C, and 1D. As the figure indicates, the slight variations in drawdowns resulting from the different pumping behaviors of the surface water diverters had no bearing on pumping at well 1,7,5.

Well 2,10,8 pumped at a consistently higher rate than any other well in the system. Its position in the lower layer of the aquifer system insulated it somewhat from the immediate effects of drawdowns produced by pumping wells in layer one. Although this well pumped more than well 1,7,5 in every time period for all the management models, the hydrologic conditions at node 2,10,8 prevented drawdowns from ever reaching or exceeding 9.0 feet. Consequently, none of the pumping restrictions involving a breach of the critical head elevation (for OSIM and SSIM) were applied at this well.

In general, the same logic used in the discussion for well 1,7,5 can be applied to the pumping rate plots for well 2,10,8. The transmissivity change (.300 to .200 ft^2/s) at this node from the A scenarios to the B scenarios had a negligible effect on pumping rates (see Figures B16 through B18).

6.3 DRAWDOWN PLOTS (Appendices C and D)

Figures C1 through C48 (Appendix C) illustrate drawdown in feet for each of the three management systems for selected nodes in the model area and for each scenario (1A-9). Figure 12 shows the distribution of the aquifer nodes for which drawdowns are plotted. The plots in Appendix D (Figures D1-D14) compare the results of ten scenarios (1A-7) for each management model for each node shown in Figure 12. A few characteristic trends common to all of the drawdown plots describe the basic results of the simulations:

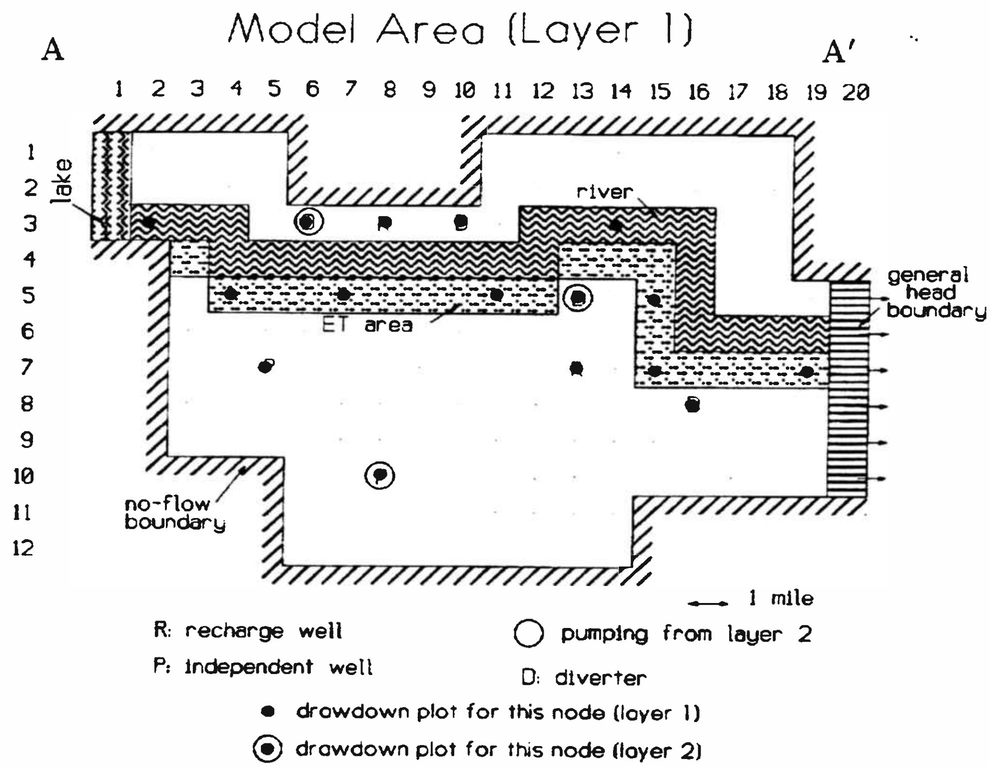


Figure 12

Nodes for Which Drawdown Plots Were Generated

<u>Pattern</u>	<u>Explanation</u>
(scenario)	
• 1A > 2A 4A > 5A	More negative α_{agric} lowers demands, reduces pumping ($D = P^{\alpha}$).
• 1A > 4A 2A > 5A	Zero water rights in second half of year reduce pumping, increase recharge, permit recovery of water table.

- $1A < 6$ — Increased surface water demands lead to more pumping.
  $2A < 7$

- $1A > 1B$ — Higher values and increased zonation of transmissivity produce smaller drawdowns for comparable pumpages.
  $2A > 2B$
  $4A > 4B$
  $5A > 5B$

- OSIM $\geq$ SSIM — (scenarios 1A - 7 only) SSIM shuts down well 1,7,5 while OSIM only increases cost of groundwater to discourage pumping.

- OSIM > GSIM — GSIM utilizes surface water return flow; priority system sensitive to available water supplies.

- SSIM < GSIM — (scenarios 1A-7 only) SSIM shuts down well 1,7,5 to reduce drawdowns over entire system.

- SSIM > OSIM — (scenarios 8 and 9 only) lower price for agricultural-use groundwater in SSIM than in OSIM. Mandatory recharge in OSIM.

- $8, 9 << 1A - 7$ — No independent pumping wells present.

In order to maintain continuity, the results for well 1,7,5 will be discussed in detail, and the reader may extend the same reasoning to plots for the remaining wells.

Figure C25 illustrates the stark contrast in the aquifer's drawdown behavior at well 1,7,5 between simulations incorporating different transmissivity distributions (Figures C25a and c vs. Figures C25b and d). As explained above for the pumping rates at this well, the smaller drawdowns resulting from transmissivity distribution 2 (Figure 10b) precludes any changes in groundwater price or any restrictions that would reduce pumping in order to curb drawdown. Scenarios 1A, 2A, 4A, 5A, 6, and 7, however, incorporate transmissivity distribution 1 (Figure 10a), and the resulting drawdowns rapidly reach the critical head elevation (i.e., 10 feet of drawdown) for the SSIM and OSIM models. After time period 3 in Figure C25a, OSIM and SSIM drawdowns begin fairly cyclic patterns of fluctuations which reflect the management systems' attempts to to reduce pumping at that well in order to prevent excessive drawdowns. The high magnitude fluctuations for the SSIM case stems from that system's total and abrupt discontinuance of pumping at well 1,7,5 when drawdowns exceed 10.0 feet. The corresponding fluctuations in the OSIM simulation are considerably smaller because pumping rates are merely reduced through price incentives instead of through the forceful shutting down of the well.

While the level of drawdown decreases from simulation 1A to 1B and from 2A to 2B for the GSIM model, no pronounced fluctuations in drawdown occur because the system imposes no restrictions on pumping. As Figures C25b and d show, in the absence of pumping limitations for OSIM and SSIM, drawdowns for those two models exceed those for GSIM. When the management system does curtail pumping, as SSIM and OSIM do in scenarios 1A and 2A, drawdowns in GSIM end up being greater than those in the other two models.

The magnitude of the drawdown fluctuations for the OSIM model increases from scenario 1A to 2A due to the change in α_{agric} from -0.5 to -1.0. Thus, when the same price increase occurs in both scenarios, the corresponding effect on demand is stronger in the 2A case (see Equation 16), and the reduction in pumping is greater. Figure C25a clearly shows that OSIM maintains an overall higher level of drawdown at node 1,7,5 than SSIM, and its drawdowns fluctuate above and below those of GSIM.

The drawdown plots for SSIM in Figures C25a and c correspond directly to the pumping plots in Figures B13a and c. Drawdowns in Figure C25a were lowest during the six time periods when the well was completely shut off (see Figure B13a, time periods 6, 8, 10, 12, 14, and 16). Although Figure B13a shows pumping rates for SSIM at higher levels than for OSIM in the first half of each year, the comparatively low SSIM drawdowns in Figure C25a reflect the recovery of head levels after discontinued pumping in the second half of years 3 - 8.

The three time periods of zero pumping for SSIM (see Figure B13c) produce the three minimum drawdown peaks for SSIM in scenario 2A (Figure C25c). The several times that SSIM drawdowns fell between 9.0 and 10.0 feet (the threshold interval) triggered lower, non-zero pumping rates (see Figure B13c), which then produced smaller-scale fluctuations in drawdowns compared to those in scenario 1A. Interestingly, the slight drop in pumping rates (for this and all agricultural wells) from scenario 1A to 2A reduced drawdowns just enough to keep the well <u>operating in more time periods</u> for scenario 2A than in 1A. For example, compare the drawdowns for time period 7 in the SSIM simulations 1A and 2A (see Table 3b and Figures C25a and c). In response to a more negative α_{agric}, drawdowns in scenario 2A fluctuate more but maintain a slightly lower level compared to those in scenario 1A until time period 7. At that point, drawdown for SSIM scenario 1A exceeds 10.0 feet, triggering the well to shut down, while the smaller drawdown in scenario 2A permits the well to continue operating. The patterns of drawdown fluctuations continue to meet and diverge, with the same type of situation reoccurring in time periods 11 and 15.

The overall flattening trend displayed in the drawdown plots, as well as those for pumping and river leakance, illustrates the effect of the system reaching a quasi-steady state as water is captured from various boundary and internal sources.

The drawdown plot for simulation 2A in the GSIM model (Figure C25) displays a somewhat irregular behavior in the middle time periods of that simulation. The irregular changes in slope between time periods 7 and 10 can be attributed to incremental changes in lift costs as lift in that well increased from its original 30 feet (see discussion under "GSIM - 1,7,5 Pumping").

The same logic used to describe the contrast between the plots in Figure C25 applies to those in Figure C26. The divergence of OSIM pumping rates between scenarios 2A and 5A after time period 17 (see Figures B13c and B14c) manifests itself in similar changes in the drawdown plots of Figures C25c and C26c.

Figure C27a illustrates drawdowns for scenario 6. The SSIM curve makes a downward adjustment in time period 4 as pumping rates decline in response to a breach of the threshold level of 9.0 feet of drawdown (see Figure B15a and Table 4a). While SSIM drawdowns maintain a level between 9.0 and 10.0 feet (time periods 4 through 12), pumping rates remain at a reduced level of about 1.5 cfs. As drawdowns gradually increase and finally break through the 10.0 foot critical head barrier, SSIM shuts down the well (see Figure B15a, time period 13), and drawdowns recover to just over 5 feet (Figure C27a).

OSIM drawdowns for scenario 6 begin a regular, cyclic fluctuation in time period 5 after exceeding 10.0 feet for the first time. Figure B15a shows the corresponding drop in OSIM pumping rates in response to higher groundwater costs when drawdowns exceed 10.0 feet. The cyclic behavior of OSIM drawdowns in Figure C27a reflects the recovery of hydraulic head back to a level below 10.0 feet, followed by an increase in pumping that accompanies the lower groundwater prices afforded by the smaller drawdowns.

GSIM drawdowns approach a quasi-steady state around time period 12, and show a mild decreasing trend in later time periods. The pumping restrictions imposed by OSIM and SSIM in this scenario result in GSIM having the largest drawdowns of all three systems for 8 out of the 20 time periods in simulation 6.

Scenario 7 drawdowns (Figure C27b) mimic the drawdowns patterns of scenario 2A (Figure C25c). As Table 4b indicates, the slight increase in drawdowns produced by heightened surface water stress on the system in scenario 7 compared to scenario 2A produce no changes significant enough to influence the pumping behavior of well 1,7,5.

Scenarios 8 and 9, shown in Figures C27c and d demonstrate the significance of pumping in the independent wells 1,7,5 and 2,10,8 for scenarios 1A - 7. Without these wells, drawdowns fall more than two orders of magnitude, and the the order of largest to smallest drawdown changes among the three model systems. Where OSIM produced the largest drawdowns in scenarios 1A - 7 (those including independent pumping wells), the largest drawdowns in scenarios 8 and 9 occur in the SSIM simulations, followed by OSIM and then GSIM. This reversal reflects the lower price of groundwater for agricultural use in SSIM ($\frac{1}{4}$ of urban groundwater price) compared to OSIM ($\frac{1}{2}$ of urban groundwater price) which stimulates more pumping from the SSIM agricultural wells. As long as drawdowns do not threaten the critical head elevation, SSIM makes no attempt to reduce pumping. Another factor contributing to the lower OSIM drawdowns is that system's practice of recharging a small percentage of the surface water inflow to the system, even though deliveries to diverters may be reduced as a result. GSIM's drawdown curve plots roughly parallel to those of SSIM and OSIM in scenario 8, but is slightly lower in magnitude in every time period. While all three drawdown curves reveal smaller drawdowns in scenario 9 (compared to 8), the GSIM curve departs from the OSIM and SSIM slopes in the first time period, and maintains a much flatter slope throughout the 20 time period simulation. This contrast in behavior is linked to the fact that two of the four diverters in SSIM and OSIM (nodes 3,6 and 5,13) are treated as urban users ($\alpha_{urban} = -0.5$), while all four GSIM diverters are considered agricultural ($\alpha_{agric} = -1.0$). The larger (less negative) elasticity of demand for urban diverters in scenario 9 leads to higher pumping rates in those nodes than for their GSIM counterparts.

Comparison of drawdowns for nodes 1,3,8 (Figures C4-C6) and 2,3,6 (Figures C40-C42) shows that drawdowns in both aquifer layers respond about equally to pumping stresses in both layers. Node 1,3,8 received recharge during some time periods, which helped offset the effects of pumping in other wells of the system. Drawdowns in wells 2,3,6 (serving an urban diverter) clearly responded to the pumping changes at well 1,7,5 after time period 5 (see Figure C40A).

The evapotranspiration node 1,7,19, at the far right (eastern) edge of the aquifer system even shows evidence of the shut down of well 1,7,5. While the effects on drawdowns illustrated in Figures C34a, C35a, and C36a are quite dampened by distance, the departure of the SSIM drawdown curve from the other two curves is still visible in later time periods of the simulations 1A, 2A, 4A, and 6.

Figures D1 through D14 (Appendix D) present the same information shown in Appendix C but in a different format. For all of the nodes illustrated in Figures D2 through D14, the following patterns persist for GSIM and OSIM:

- Scenarios plot in groups: (1A, 4A, 6), (2A, 5A, 7), (1B, 4B), and (2B, 5B).

- In general, the scenario "groups" produce drawdowns in order of highest to lowest: (1A, 4A, 6) > (2A, 5A, 7) > (1B,4B) > (2B, 5B).

- The scenario groups maintain a fairly regular spread (i.e., equidistant from one group to the next) in the GSIM plots, with the regularity and magnitude of spacing between the groups decreasing somewhat in OSIM.

- Scenarios 2B and 5B consistently produce downward-curving plots in later time periods (after time period 11, for example), while the other eight scenarios tend to plot in monotonically increasing to flattening curves.

SSIM plots abide by some of the trends listed above, but with several exceptions. First, scenario 6 plots above the 1A and 4A curves for this management system. (see Figure D2c, for example). The scenario 6 drawdown curve breaks from its original curve and begins an irregular decline starting in time period 13. Scenarios 1A and 4A still plot as a pair, with the 1A curve slightly above the 4A curve. This pair of curves begins a cycle of fluctuations around time period 6, but maintains an increasing trend throughout the course of the simulation (refer to Figure D3c). The (2A, 5A, 7) scenario group plots together, but also displays a cyclic pattern of fluctuations after about time period 6. As in GSIM and OSIM, this group of plots generally falls between the (1A, 4A) group and the (1B, 4B) group. The last two groups, (1B, 4B) and (2B, 5B) behave essentially the same as the corresponding curves for OSIM. These four scenarios were unaffected by pumping restrictions because of smaller drawdowns produced with transmissivity distribution 2 (see Figure 10b).

Figure D9 displays the drawdown plots for well 1,7,5. In Figure D9a, the top two curves represent scenarios incorporating transmissivity distribution 1, while the lower two curves represent those using transmissivity 2. The obvious decrease in drawdowns from transmissivity distribution 1 to 2 makes the difference between the OSIM and SSIM scenarios which experience pumping restrictions and those which do not. Figure D9b illustrates the clear pattern of increasing and decreasing pumping rates in response to OSIM's price incentive plan to prevent excessive drawdowns. In the top two groups of plots of Figure D9b (scenarios (1A, 4A, 6) and (2A, 5A, 7)), drawdowns exceed 10 feet in most of the even-numbered time periods. These breachings of the critical head level (10 feet below initial head) result in higher groundwater costs and subsequently, lower pumping rates in the odd-numbered time periods. Reduced pumping in the odd-numbered time periods, in turn, permits aquifer head levels to rebound to a level above the critical head elevation, thus triggering a return to lower groundwater prices and higher pumping rates.

Figure D9c displays a complicated set of drawdown curves for SSIM scenarios 1A-7 at well 1,7,5. The separation between the transmissivity distribution 1 scenarios and the transmissivity distribution 2 scenarios is less distinct than for the other two management systems. As a consequence of shutting down the well when drawdowns reach 10 feet or more, several scenarios (1A, 4A, 6, 2A, 5A, and 7) end up having recovery drawdowns comparable to those for the transmissivity distribution 2 scenarios (1B, 2B, 4B, and 5B). In general no one scenario (out of the transmissivity 1 scenarios) produces distinctly higher or more prolonged drawdowns than any other. This result counters the trends displayed in plots for the other two management systems. The transmissivity 1 scenarios with $\alpha_{agric} = -1.0$ (2A, 5A, and 7) were generally less volatile in the magnitude of their drawdown fluctuations, but nevertheless, displayed a wide range of variation between consecutive time periods.

The plot for river node 1,3,2, shown in Figure D1, exhibits a trend unique from all of the other plots in Appendix D. In this node, the scenarios groups, ranked in order of highest to lowest drawdown are: (1B, 4B) > (2B, 5B) > (1A, 4A, 6) > (2A, 5A, 7). Reference to Figures 11 and 12 reveals a two-fold increase in transmissivity at node 1,3,2 from scenarios 1A, 2A, 4A, 5A, 6, and 7 (Figure 10a) to scenarios 1B, 2B, 4B, and 5B (Figure 10b). Such an increase in transmissivity, alone, would be expected to produce smaller drawdowns in the latter group of scenarios. However, the layer 2 transmissivity at this node decreases by a factor of 2 in Figure 10b. In fact, several other nodes have lower layer 2 transmissivities in Figure 10b than in Figure 10a. The complex superposition of all of the effects of the new transmissivities across the aquifer system produce the unexpected, but feasible, result seen at river node 1,3,2.

6.4 TRANSECT PLOTS

Figures 13 through 16 show layer one drawdowns along the west-east transect A-A′ (see Figure 12) for three time periods (1, 10, and 20) in scenarios 1A, 1B, 2A and 2B for all three management models. All of the graphs in the four figures share the common trait of a drawdown maximum at or near column 6, trailing off from that column eastward. The locations of the two most productive wells, nodes 1,7,5 and 2,10,8, contribute significantly to the observed trends.

The contrast between Figures 13 and 14 and between Figures 15 and 16 illustrates two subtle differences between scenarios incorporating transmissivity distribution 1 (Figure 10a) versus those with transmissivity distribution 2 (Figure 10b). Scenarios 1B and 2B (Figures 14 and 16) exhibit a slight eastward shift of the maximum drawdown column compared to scenarios 1A and 2A. Also, the 1B and 2B drawdowns dip more sharply from column 8 to column 12 instead of showing the gradual decrease of those in Figures 13 and 15. The second distribution consists of larger magnitude and more heavily zoned transmissivities than the first. Typically, one would expect smaller drawdowns and more abrupt changes in drawdowns to accompany such changes.

The transect plots display a dramatic increase in drawdowns between time periods 1 and 10 followed by a slight recovery (decrease in drawdowns) from time period 10 to 20 in most cases. On the other hand, drawdowns actually increase slightly from time period 10 to 20 for scenario 1A (Figures 13b and c), with the increase being strongest in the SSIM case.

In all cases, drawdowns for all three management models are identical for the first time period. By time period 10, some divergence has occurred between the plots. For scenarios 1A and 2A (Figures 13 and 15), the SSIM curve drops well below the OSIM and GSIM curves in response to the shut down of well 1,7,5. The OSIM and GSIM curves maintain nearly identical levels, with GSIM falling slightly below the OSIM curve. Time period 20 for scenarios 1A and 2A shows little change in the GSIM and OSIM curves, but the OSIM curve now falls slightly below the GSIM because of price incentives imposed by OSIM to reduce pumping at well 1,7,5. SSIM drawdowns still fall below those of GSIM and OSIM, but the have increased from their time period 10 levels, and come closer to being parallel with the other two curves.

Figures 14 and 16 show the case to be somewhat different for scenarios 1B and 2B. For these scenarios, drawdowns remain small enough at well 1,7,5 to preclude any restrictions on pumping there. As a result, SSIM drawdowns slightly exceed those for OSIM (recall that SSIM wells pump more because of cheaper agricultural-use groundwater compared to OSIM), but the two curves are hardly distinguishable in time

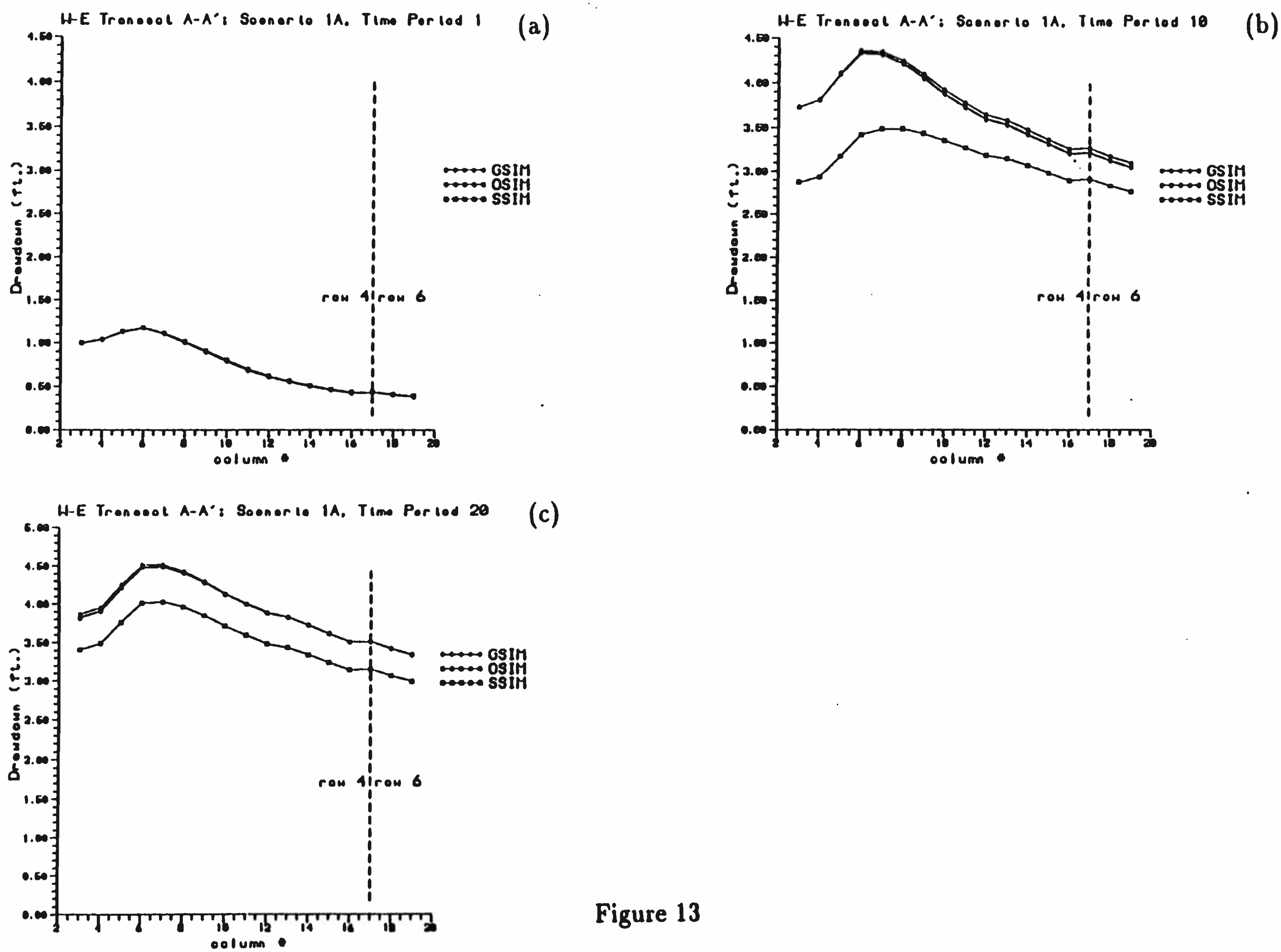
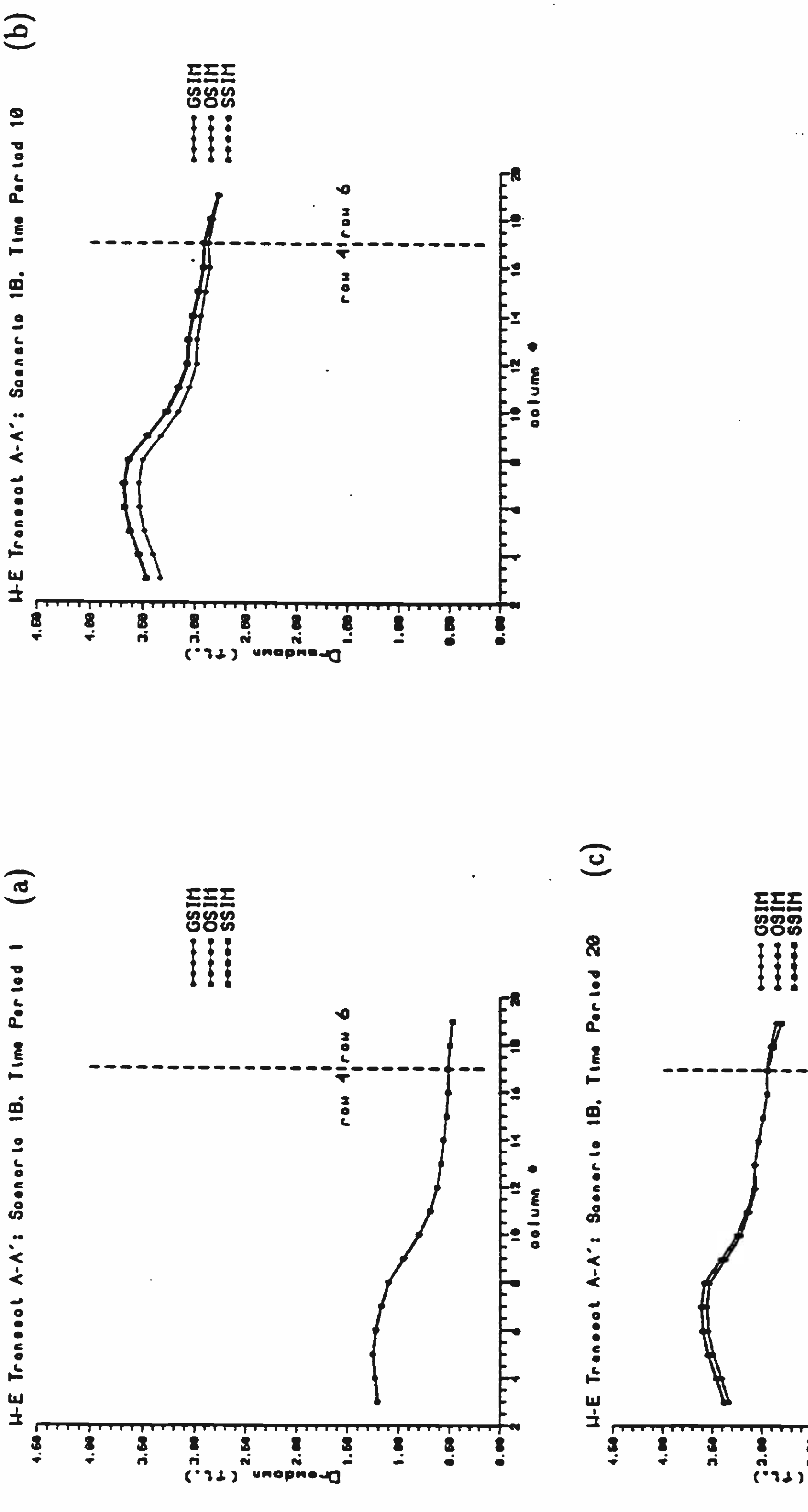

W-E Transect A-A'; Scenario 1A, Time Period 1
(a)
Drawdown (ft.)
column #
row 4 | row 6
GSIM
OSIM
SSIM
W-E Transect A-A'; Scenario 1A, Time Period 10
(b)
Drawdown (ft.)
column #
row 4 | row 6
GSIM
OSIM
SSIM
W-E Transect A-A'; Scenario 1A, Time Period 20
(c)
Drawdown (ft.)
column #
row 4 | row 6
GSIM
OSIM
SSIM

Figure 13



(a)
W-E Transect A-A': Scenario 1B, Time Period 1
GSIM
OSIM
SSIM
row 4
row 6
Drawdown (ft.)
column #
(b)
W-E Transect A-A': Scenario 1B, Time Period 10
GSIM
OSIM
SSIM
row 4
row 6
Drawdown (ft.)
column #
(c)
W-E Transect A-A': Scenario 1B, Time Period 20
GSIM
OSIM
SSIM
row 4
row 6
Drawdown (ft.)
column #

Figure 14

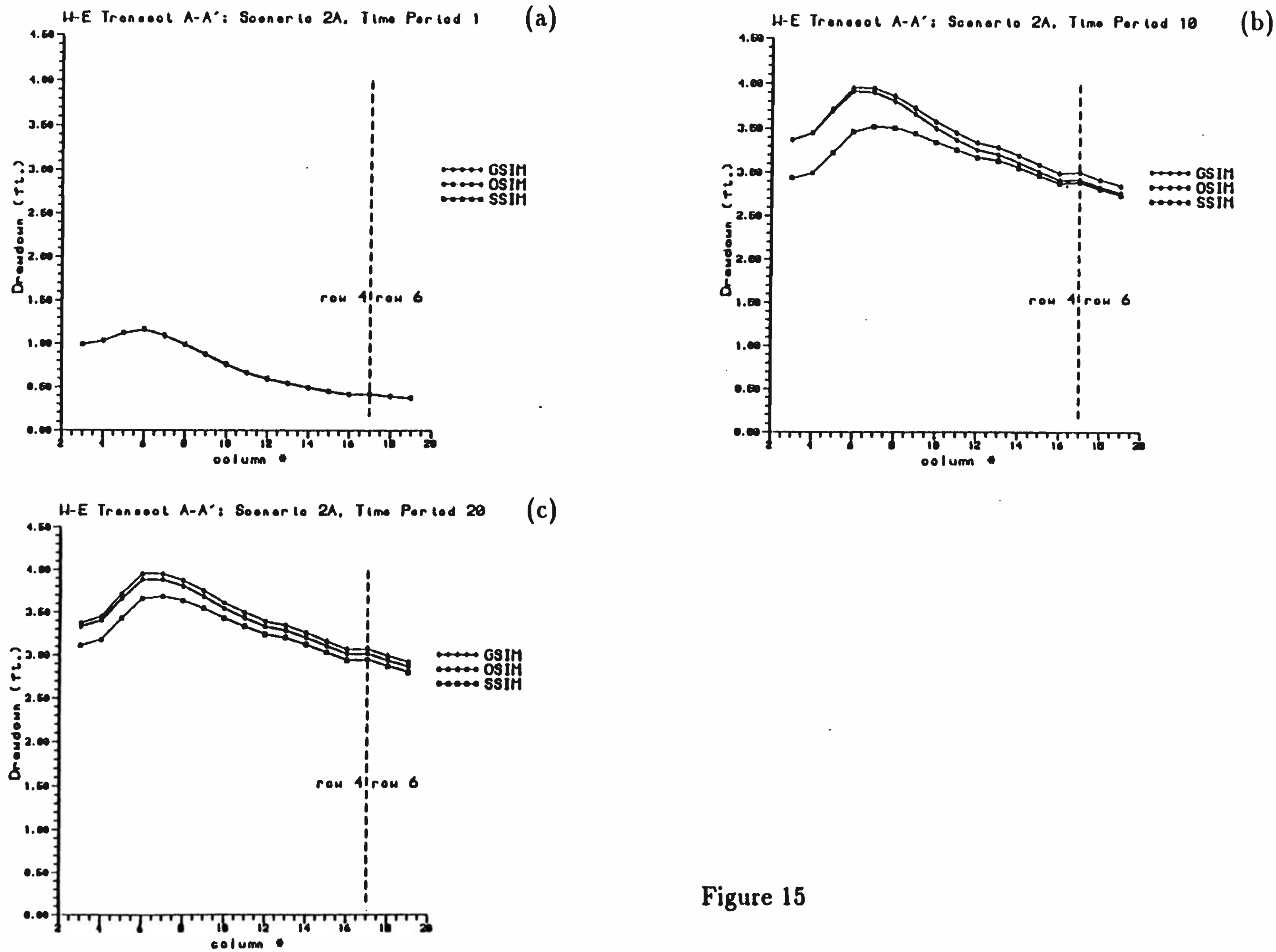

W-E Transect A-A'; Scenario 2A, Time Period 1
(a)
Drawdown (ft.)
column #
GSIM
OSIM
SSIM
row 4
row 6
W-E Transect A-A'; Scenario 2A, Time Period 10
(b)
Drawdown (ft.)
column #
GSIM
OSIM
SSIM
row 4
row 6
W-E Transect A-A'; Scenario 2A, Time Period 20
(c)
Drawdown (ft.)
column #
GSIM
OSIM
SSIM
row 4
row 6

Figure 15

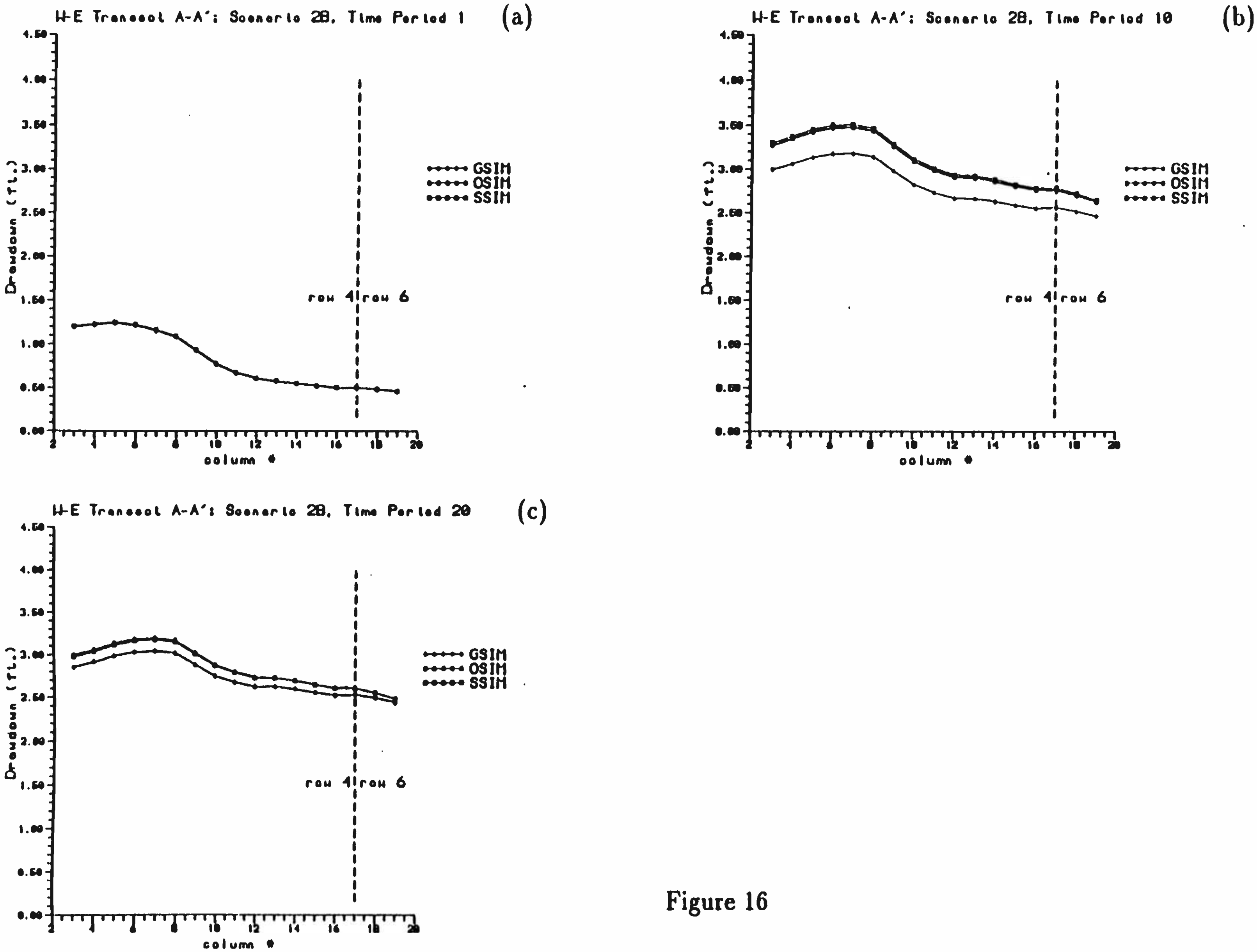

W-E Transect A-A'; Scenario 2B, Time Period 1
(a)
W-E Transect A-A'; Scenario 2B, Time Period 10
(b)
W-E Transect A-A'; Scenario 2B, Time Period 20
(c)
Drawdown (ft.)
column #
GSIM
OSIM
SSIM
row 4
row 6
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
2
4
6
8
10
12
14
16
18
20

Figure 16

period 10. The GSIM curve, however, is distinctly below the other two curves over most of the model area. By time period 20, the OSIM and SSIM curves appear nearly identical, and have dropped to a slightly lower level. GSIM drawdowns have increased from their time period 10 levels, and actually exceed those for OSIM and SSIM east of column 17 in scenario 1B (Figure 14c).

6.5 RIVER CAPTURE PLOTS (Appendix E)

In form, the river capture curves in Figures E1 through E27 correspond exactly to the plots of drawdown vs. time in Appendix C. Figure 17 illustrates the selected nodes for which river capture plots were generated. River node 1,4,7 (Figures E10-E12) produced the highest volume of water captured through the riverbed. The proximity of this and other adjacent river nodes to several pumping wells resulted in the comparatively high volume of capture from these cells. The effects of reduced and discontinued pumping in well 1,7,5 during SSIM and OSIM scenarios 1A, 2A, 4A, 5A, 6, and 7 show up quite clearly in plots of river capture vs. time even in nodes on the far east (right) end of the aquifer system (see Figures E25-E27 for river node 6,19, for example). All of the resultant river capture values for scenarios 1A - 9 can be understood by applying the same logic as used in the discussion of the drawdown plots in the previous section.

6.5.1 Nonlinear Cases

The direct correspondence between river capture and drawdown reflects the linearity of the hydrologic system. River capture response functions are multiplied by pumping rates and summed according to Equation 7 in the same manner as for incremental drawdowns in Equation 2. While the provision for calculating river capture in nonlinear cases where drawdown exceeds the bottom

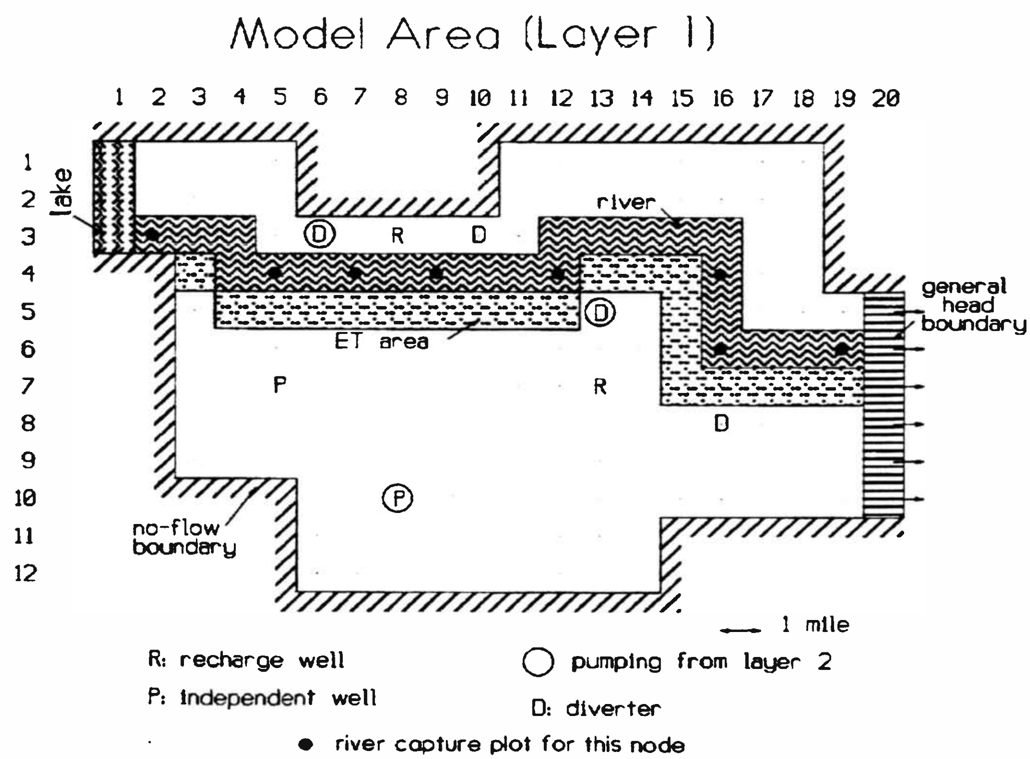


Figure 17

Nodes for Which River Capture Plots Were Generated

of the riverbed exists in the simulation programs (see discussion under "Nonlinear Case 1"), none of the scenarios in this study produced such a circumstance.

Six scenarios, shown in Table 6, produced nonlinear capture from ET nodes in the OSIM management system. In all of the simulations, ET node 1,7,19 was the only node where the linearity condition was violated. (Please refer to the discussion under the heading "Nonlinear Case 2" in Chapter 3 for details on the calculation of ET capture under nonlinear conditions.) The lower drawdowns in the same scenarios for

GSIM and SSIM prevented any nonlinear ET capture.

6.6 RECHARGE PLOTS (Appendix F)

The wells at nodes 1,3,8 and 1,7,13 serve as injection wells for artificial recharge to the system (see Figure 9). Appendix F Figures F1 through F6 plot injection rates vs. time for the two recharge wells. Figures F1 (well 1,3,8) and F4 (well 1,7,13) include graphs for scenarios 1A, 1B, 2A, and 2B. Since GSIM recharges only during non-irrigation seasons (when surface water rights are set to 0.0), GSIM curves appear only in plots for scenarios 4A, 4B, 5A, and 5B (Figures F2 and F5). Scenarios 6 and 7 are plotted in Figures F3 and F6.

Figures F1a and c show very similar recharge patterns for OSIM and SSIM wells at node 1,3,8 during scenarios 1A and 2A. Although difficult to resolve from the graphs, the OSIM recharge rates are slightly higher (non-zero) than the SSIM rates during time periods 1-3 and 8-12. The strong peak in time period 5 coincides with the time of highest surface water supply (see Figure 11) and fulfilled surface water demands (see diversion plots in Figure A1). In that case, both OSIM and SSIM recharged all of the excess surface water to well 1,3,8. In time period 7, however, the OSIM and SSIM recharge curves depart. Even though both systems had the same volume of water to recharge, the drawdowns in the two simulations were sufficiently different to produce different recharge behaviors. SSIM recharged its water through well 1,7,13 (see Figure F4a) while OSIM recharged through well 1,3,8. In both cases, the choice of recharge location was based on which of the two wells had the largest drawdown from its original head level.

After time period 12, both systems recharged exclusively to well 1,7,13. Figure F4a shows another strong peak in recharge rates coinciding with the high surface water

OSIM Simulations Violating Linearity Condition
at ET Node 1,7,19

time period	1A	2A	4A	5A	6	7
1						
2						
3						
4						
5						
6						
7						
8						
9	X		X		X	
10	X		X		X	
11	X	X	X		X	X
12	X	X	X	X	X	X
13	X	X	X	X	X	X
14	X	X	X	X	X	X
15	X	X	X	X	X	X
16	X	X	X	X	X	X
17	X	X	X	X	X	X
18	X	X	X	X	X	X
19	X	X	X	X	X	X
20	X	X	X	X	X	X

X = linearity violation

Table 6

supply of time period 13. From time period 15 on, both systems largely failed to meet surface water demands, and SSIM ceased recharging to either of the two wells. OSIM's policy of mandatory recharge forced the system to inject some water into well 1,7,13 even during those time periods when surface water diversions were unfulfilled.

Figures F1c and F4c indicate that the small differences in drawdowns between scenarios 1A and 2A had no bearing on recharge behavior for either system. Figures

F1b and d show identical plots for scenarios 1B and 2B, as well. The contrast between scenarios 1A and 1B shows up most clearly in the plots for well 1,7,13 (Figures F4a and b). Clearly, neither system injects any water into this well in scenario 1B. The graph in Figure F1b shows a second small peak in recharge for scenario 1B at time period 13 and very small recharge rates for the remaining time periods. These differences from scenario 1A arise from the smaller drawdowns produced with transmissivity distribution 2. The same contrast appears between scenarios 1B and 2B (Figures F1c and d and F4c and d).

Scenarios 4A-5B include recharge for GSIM in the second half (non-irrigation season) of each year. Figures F2a and F5a illustrate the trend of moving from recharge 1,3,8 to 1,7,13 in later time periods. The time step 1 curves for OSIM and SSIM (solid lines connecting odd-numbered time periods) remain unchanged from the scenario 1A plots (Figures F1a and F4a). The time step 2 lines (dashed) in Figure F2a show the same recharge rates for well 1,3,8 in all three management systems for the first three years, with SSIM diverging first in time period 10 (its recharge goes to well 1,7,13), and OSIM departing from GSIM in time period 12 (refer to Figure F5a). In time period 16, GSIM follows suit and moves its recharge operation to well 1,7,13. All three management systems recharge equal volumes of water during the second half of each year because all surface water rights are set to zero in these time periods.

Figures F2b and F5b show that GSIM's recharge behavior was influenced by the differences in drawdowns between scenarios 4A and 5A. Since all of GSIM's diverters are agricultural, changing α_{agric} from -0.5 to -1.0 (scenario 4A to 5A) had a more profound impact on pumping, and thus drawdowns, in GSIM compared to the other two systems. With smaller drawdowns, head levels in well 1,3,8 recovered more quickly after the initiation of recharge, and GSIM proceeded to shift its recharge to well 1,7,13 at an earlier time period than in scenario 4A.

Recharge plots for scenarios 4B and 5B reflect identical recharge behaviors for all three management systems in the second time step of each year. In odd-numbered time periods, OSIM and SSIM recharge patterns behaved exactly as they did in scenarios 1B and 2B. Recharge in the second half of each year naturally exceeds that in the first half because of zero surface water rights in time step 2 of each year.

Figures F3a and b and F6a and b show recharge rates for OSIM and SSIM in scenarios 6 and 7, respectively. In general, the higher demands on surface water in these scenarios compared with the previous ones forces both systems to reduce recharge. Again, recharge begins with well 1,3,8 and shifts to well 1,7,13 as heads recover in the former well. Figures F6a and b show strong peaks in time period 14. While the surface water inflow to the system was much higher in time period 13 than in 14, the two systems fulfilled all surface water rights in both time periods. Smaller surface water rights in time period 14 than in 13, however, left more water for recharging in that time period.

While OSIM recharged more water than SSIM in most cases, SSIM's recharge actually exceeded OSIM's in time period 14 for both scenarios 6 and 7. Oddly, since the formula for distributing surface water among rights holders in times of shortage (in OSIM and SSIM) incorporates the volume of each user's diversions over the previous three years, the mandatory recharge requirement (which gave OSIM diverters slightly less water than SSIM diverters in most time periods) ended up permitting somewhat higher diversions to OSIM agricultural users in this case. Larger diversions left less water for recharging. This point illustrates one distinguishing trail of the OSIM/SSIM method for handling surface water shortages: even though surface water diversions remain unfulfilled, some water remains available for artificial recharge. In contrast, GSIM makes every attempt to satisfy surface water users, with no regard for artificial recharge during irrigation seasons.

6.7 MODFLOW COMPARISON

In order to verify that drawdown and river capture response functions were properly handled by the simulation routines (OSIM, SSIM, and GSIM), pumping rates output from OSIM and GSIM scenarios 1A were applied in a MODFLOW simulation of the model aquifer. Minor discrepancies between drawdowns in MODFLOW and the conjunctive management models reflects limitations on the number of significant digits in pumping rates supplied to MODFLOW compared to those used for calculations in GSIM and OSIM. The general conclusions reached by comparing the water budgets in each time period for the two MODFLOW simulations can be summarized as follows:

- After about the fourth time period, GSIM consistently drew more water through the constant-head boundary than OSIM. Since the supplemental water supply well for GSIM is located in node 2,2,1 (nearly on the constant-head boundary), this result shows the impact of this well's pumping on the boundary.

- In most odd-numbered time periods, when agricultural surface water rights were highest, GSIM wells extracted more water and "infiltration" recharge rates were higher than in OSIM. In the even-numbered time periods, agricultural water rights diminished (see Tables 2a and b), while the urban surface water diverters (OSIM and SSIM only) continued to divert about the same volume as before. Thus, OSIM wells pumped more and incidental recharge for OSIM diversion points exceeded that of GSIM in the second half of each year.

- After time period 8 (the end of year 4), GSIM continued to induce more leakance from through the riverbed than OSIM.

- About the same time, OSIM began losing more water to evapotranspiration and through head-dependent boundaries than GSIM. These two consequences reflect lower GSIM heads, which produced smaller vertical head gradients across the eastern boundary and less evapotranspiration.

- In the time periods where GSIM pumping and infiltration plus artificial recharge exceeded those for OSIM, the water budget for GSIM showed more water coming into storage than in OSIM.

- In all but three time periods (16, 18 and 20), OSIM water budgets showed the same (zero) or more water coming out of storage than in GSIM.

- No water entered either system through evapotranspiration or head-dependent boundaries.

Chapter 7
Conclusions

The purpose of this study was to compare the relative performances of three general conjunctive management systems. The management rules derive from those in place or planned for future implementation in Orange County and Santa Clara County, California as well as in the South Platte area of Colorado. While the systems simulated by the three computer programs OSIM, SSIM and GSIM are *not* accurate representations of any of the three real systems listed above, the computer models attempt to capture the *general managerial character* of the real systems on which they are based. The simulations described in this study do not, by any means, encompass the whole spectrum of possible scenarios. Instead, they were designed to illustrate and compare the performances of the three management models under a few different circumstances.

As its secondary purpose, this study provides a concrete example of how response functions may be incorporated into a management simulation model. While only drawdown and river capture response functions were employed here, the MODRSP program is capable of generating several other types of response functions which could easily be incorporated into the management models. In addition, this study illustrates the use of response functions for a multi-layer aquifer system, and gives examples of the effects changes in one aquifer layer may have on components (such as drawdown) in another.

The following points summarize the major findings in this study relating to *policy variables* which distinguish the three rule sets of GSIM, OSIM, and SSIM:

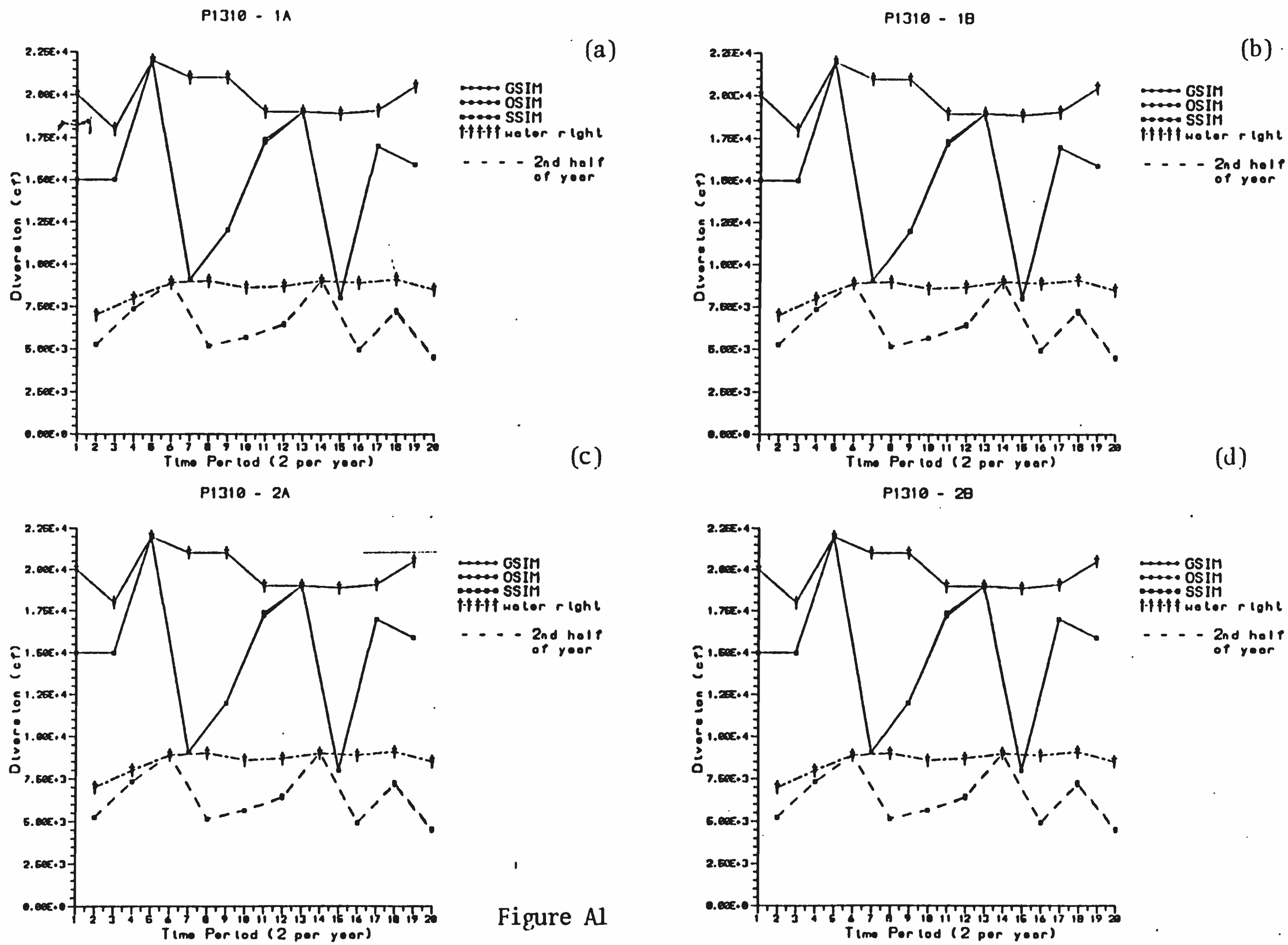

P1310 - 1A
(a)
P1310 - 1B
(b)
P1310 - 2A
(c)
P1310 - 2B
(d)
Diversion (cf)
Time Period (2 per year)
GSIM
OSIM
SSIM
water right
2nd half of year
2.25E+4
2.00E+4
1.75E+4
1.50E+4
1.25E+4
1.00E+4
7.50E+3
5.00E+3
2.50E+3
0.00E+0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure A1

of the water table. Thus, GSIM drawdowns generally equal or exceed those of OSIM, and usually exceed those of SSIM because of the shut-off policy of that system for wells whose drawdowns breach the critical head level.

By shutting down wells with excessive drawdowns, the SSIM management system maintained higher head levels than OSIM in comparable situations (see transect plots, Figures 13b and c). OSIM's use of price incentives to discourage pumping in areas of large drawdown did help slow the decline in aquifer heads, but the effects were subtle in comparison to SSIM.

- **Mandatory Recharge**

  In all cases of surface water shortage, SSIM delivered more water to diverters than OSIM because of OSIM's mandatory recharge requirement, which diminishes the volume of surface water available for delivery. In the simulations of this study, the benefit of mitigating drawdowns by artificial recharge in OSIM was outweighed by OSIM's lack of restriction on pumping rates. In general, drawdowns were higher in OSIM than SSIM.

- **Threshold vs. Critical Head**

  Table 3b and Figures B13c and C25c illustrate the mixed results of implementing the threshold concept to slow the progression of drawdowns in SSIM. By doing so, SSIM permits the well at node 1,7,5 to continue pumping at a diminished rate in some time periods, but the continued pumping still brings the head to the critical point eventually. At that time, the SSIM well shuts down, head recovers, and the cycle continues. By contrast, OSIM pumping rates fluctuate up and down as drawdowns hover near the critical

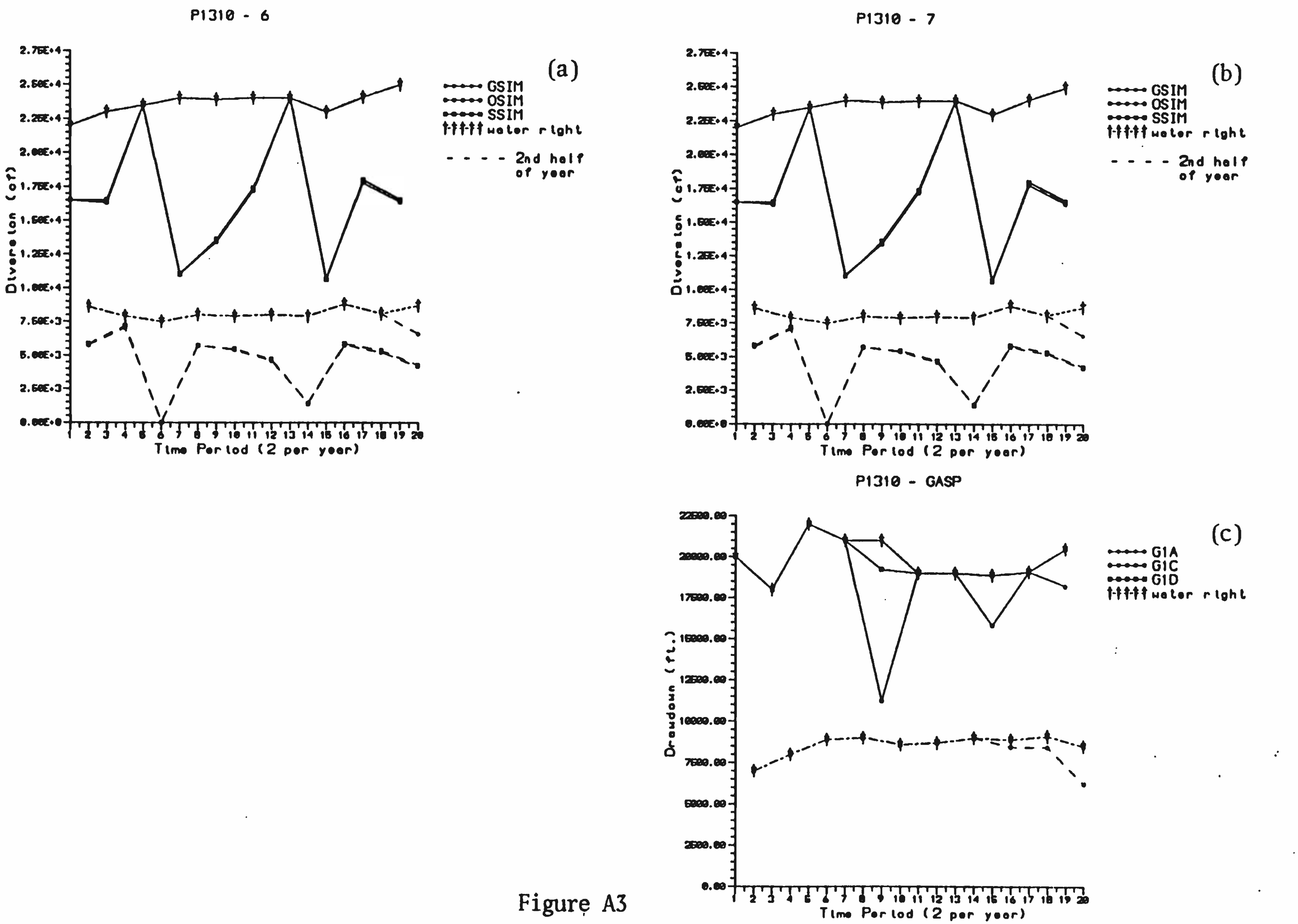

P1310 - 6
(a)
Diversion (af)
Time Period (2 per year)
GSIM
OSIM
SSIM
water right
2nd half of year
P1310 - 7
(b)
Diversion (af)
Time Period (2 per year)
GSIM
OSIM
SSIM
water right
2nd half of year
P1310 - GASP
(c)
Drawdown (ft.)
Time Period (2 per year)
G1A
G1C
G1D
water right

Figure A3

SSIM's low price for agricultural-use groundwater compared to OSIM

- **Surface Water Inflow and Required Outflow**

  GSIM's success at delivering surface water to diverters corresponded directly to the volume of surface water entering the system in the current time period. In times of surface water shortfalls, OSIM and SSIM delivered surface water to users according to a particular rule set which attempts to distribute the shortfall equitably among all of the users of the same type (eg, agricultural or urban). The rule set outlined in the section entitled "SSIM and OSIM Models in Detail", ties the percentage by which a user's diversion is cut to previous and current years' inflows as well as the average volume of water delivered to that user for the same time step over the previous three years. Thus, surface water deliveries are somewhat buffered from drastic reductions in surface water inflows to the system from the previous to the current year. However, in the event of a very slight shortfall and a larger surface water inflow in the current year than in the previous, the rule set has the undesired effect of reducing all users' diversions by *more* than the actual shortfall. OSIM and SSIM scenarios 6 and 7 produce this effect in time period 2.

- **Groundwater Costs**

  For all agricultural wells except well 1,7,5, SSIM wells pumped more than OSIM wells, and OSIM wells pumped more than the corresponding GSIM wells. These trends are linked to SSIM's lower groundwater charge for agricultural use compared to OSIM's, and GSIM's higher rate of success at meeting surface water demands among its diverters.

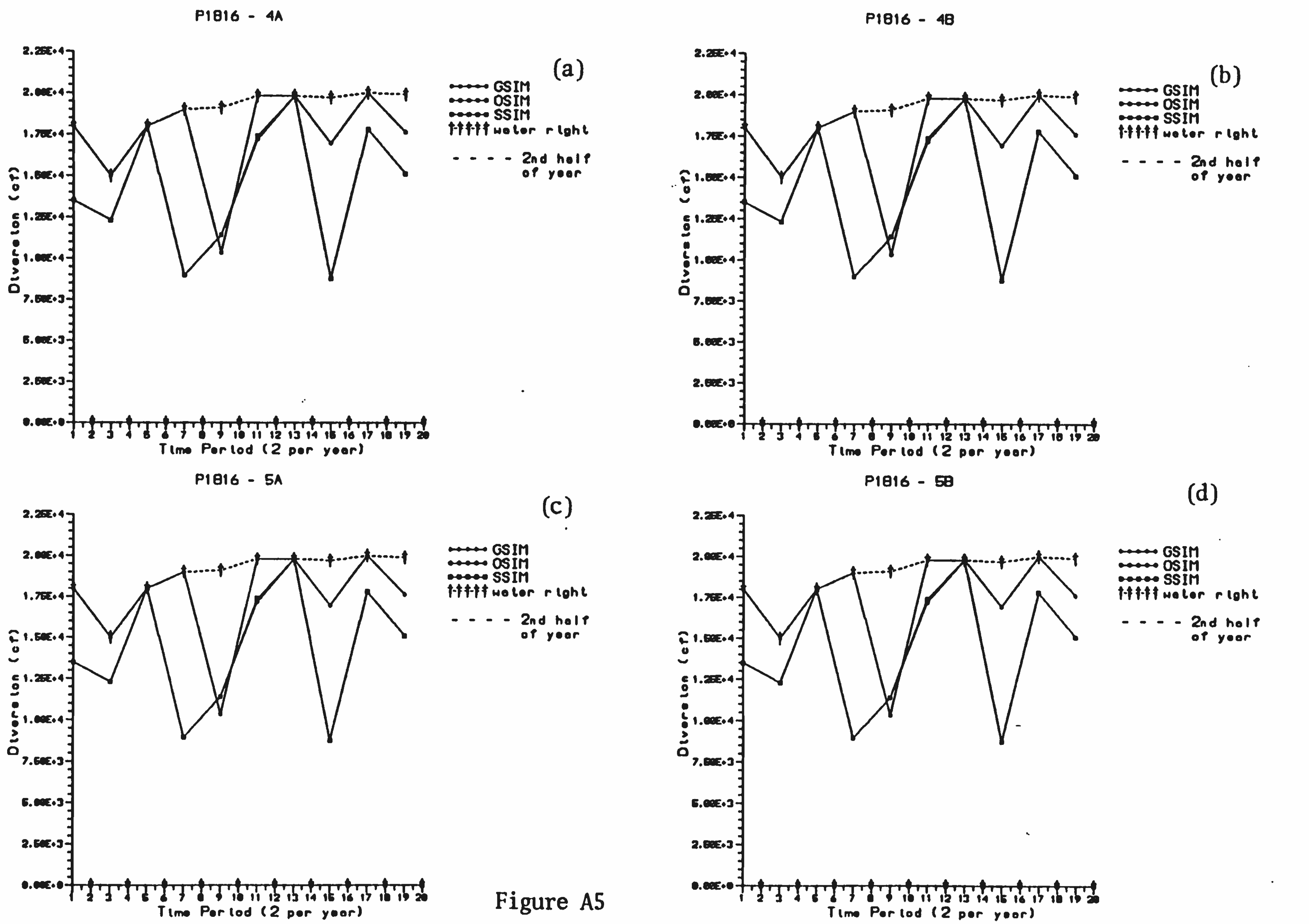

P1816 - 4A
(a)
GSIM
OSIM
SSIM
water right
2nd half of year
Diversion (af)
2.25E+4
2.00E+4
1.75E+4
1.50E+4
1.25E+4
1.00E+4
7.50E+3
5.00E+3
2.50E+3
0.00E+0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
P1816 - 4B
(b)
P1816 - 5A
(c)
P1816 - 5B
(d)

Figure A5

than others. In the event that drawdowns for a particular time period *decreased* with transmissivity distribution 2, the pumping rates at the effected nodes generally increased compared to corresponding transmissivity 1 scenarios.

- **Water Rights**

  Pumping rates in diversion node wells varied according to the user's priority and surface water right in GSIM scenarios 1A-1D. Variations in diversion priorities resulted in decreased surface water deliveries to some users, which in turn, stimulated those users to pump more.

Setting surface water rights to 0.0 cf in the second time step of each year in scenarios 4A-5B resulted in zero pumping from diversion nodes in those time periods. Eliminating pumping in these wells for one time step in each year produced very slight differences in drawdowns at fairly distant independent wells 1,7,5 and 2,10,8. In one OSIM case, however, this minute difference in drawdown (.022 ft.) determined whether or not well 1,7,5 suffered a groundwater price increase because the head at that well fell to .02 foot below the critical head level (OSIM scenario 2A, time period 17; see Table 3b). Since well 1,7,5 pumped at a comparatively high rate under normal price conditions, increasing the groundwater cost and thereby reducing demand at the well decreased drawdowns across the entire aquifer.

7.1 RECOMMENDATIONS FOR FUTURE STUDIES

This study sought to develop tools for the systematic comparison of three different conjunctive management systems. The simulations described in this thesis represent a very small set of possible scenarios for testing the relative performances of

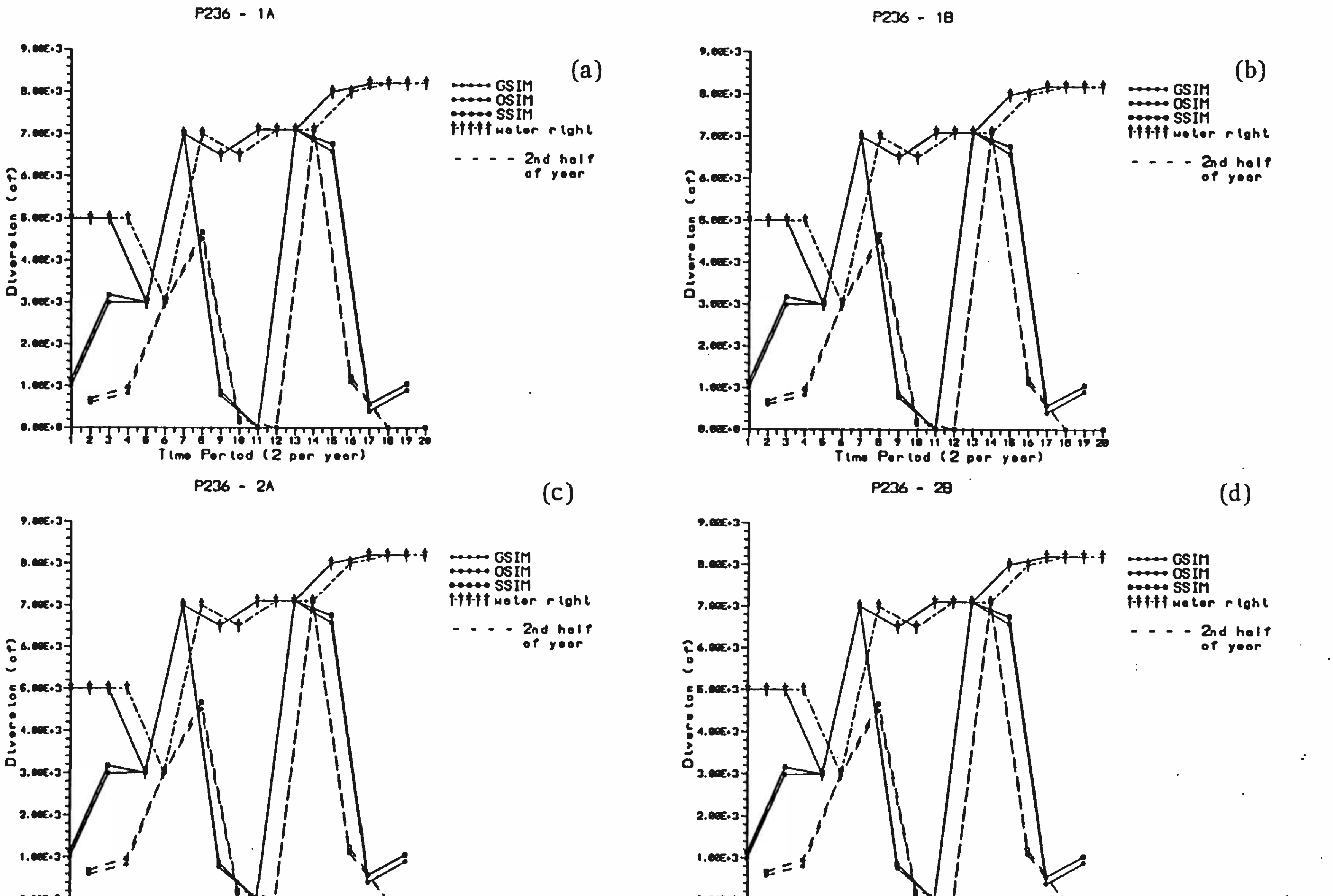

P236 - 1A
(a)
P236 - 1B
(b)
P236 - 2A
(c)
P236 - 2B
(d)
Diversion (af)
Time Period (2 per year)
GSIM
OSIM
SSIM
water right
2nd half of year
9.00E+3
8.00E+3
7.00E+3
6.00E+3
5.00E+3
4.00E+3
3.00E+3
2.00E+3
1.00E+3
0.00E+0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure A7

Chapter 8
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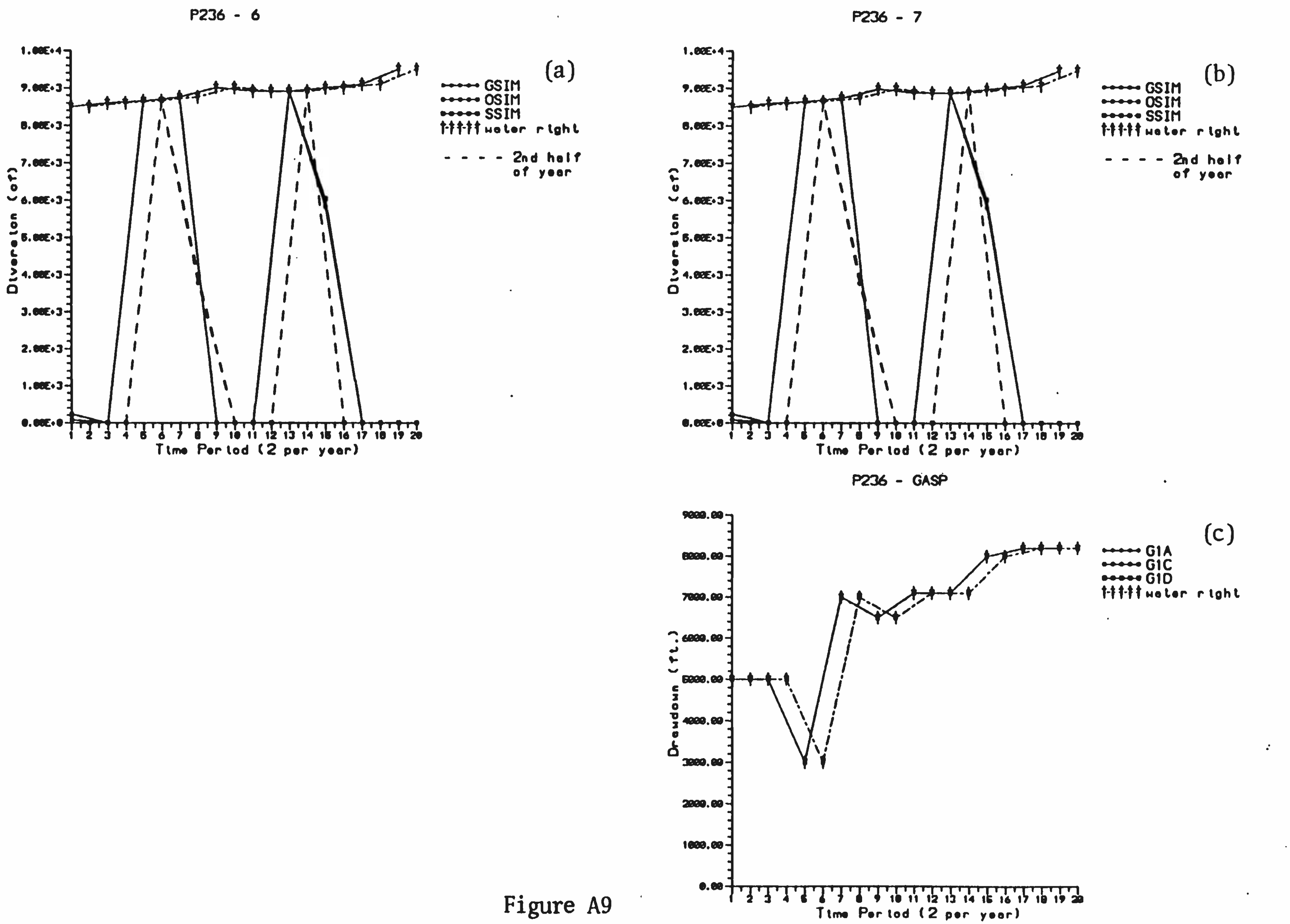
P236 - 6
(a)
GSIM
OSIM
SSIM
water right
2nd half of year
Diversion (af)
Time Period (2 per year)
P236 - 7
(b)
GSIM
OSIM
SSIM
water right
2nd half of year
Diversion (af)
Time Period (2 per year)
P236 - GASP
(c)
G1A
G1C
G1D
water right
Drawdown (ft.)
Time Period (2 per year)

Figure A9

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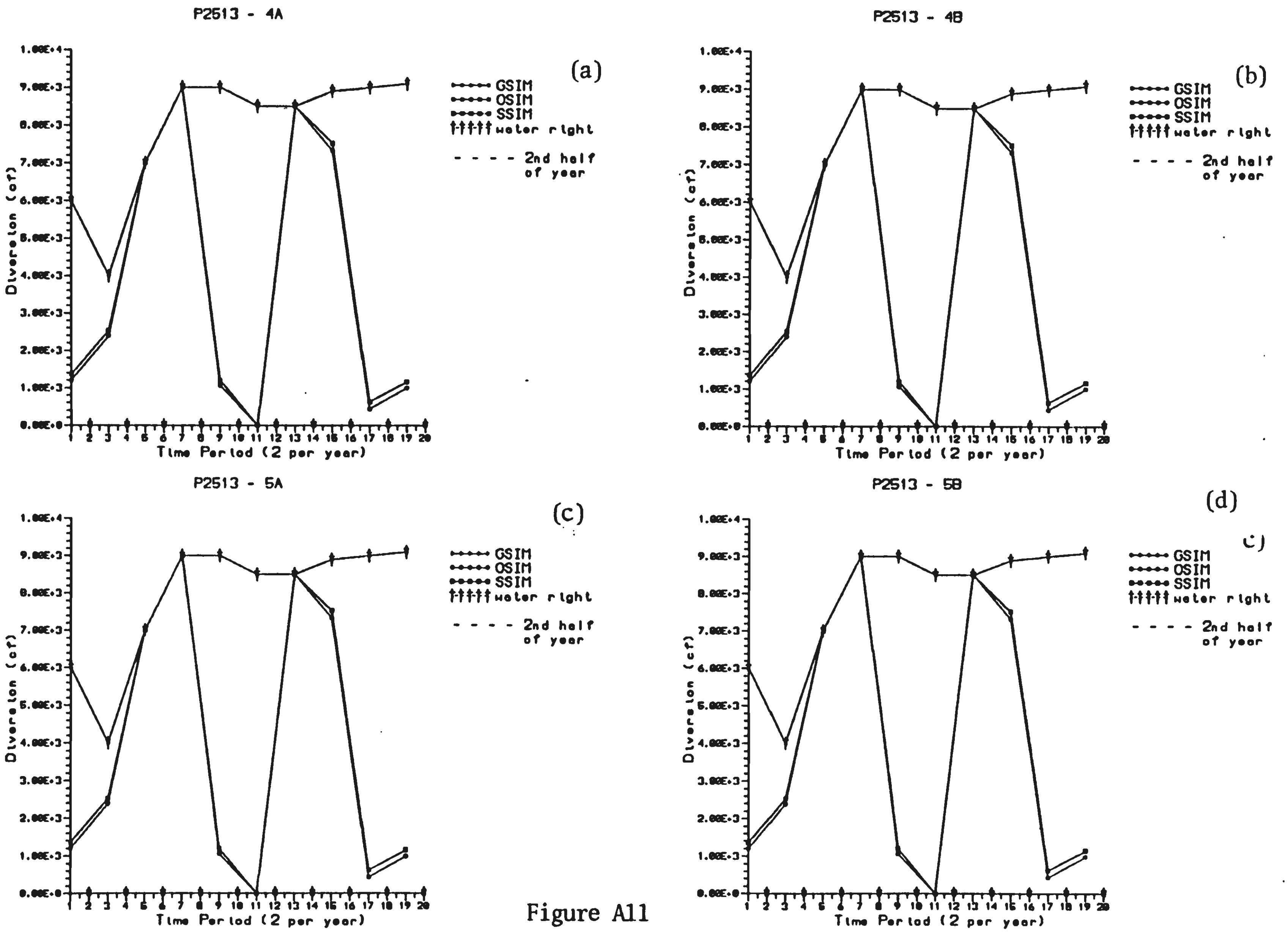

P2513 - 4A
P2513 - 4B
P2513 - 5A
P2513 - 5B
(a)
(b)
(c)
(d)
GSIM
OSIM
SSIM
water right
2nd half of year
Diversion (af)
Time Period (2 per year)
1.00E+4
9.00E+3
8.00E+3
7.00E+3
6.00E+3
5.00E+3
4.00E+3
3.00E+3
2.00E+3
1.00E+3
0.00E+0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure A11

APPENDIX A

Diversion Plots

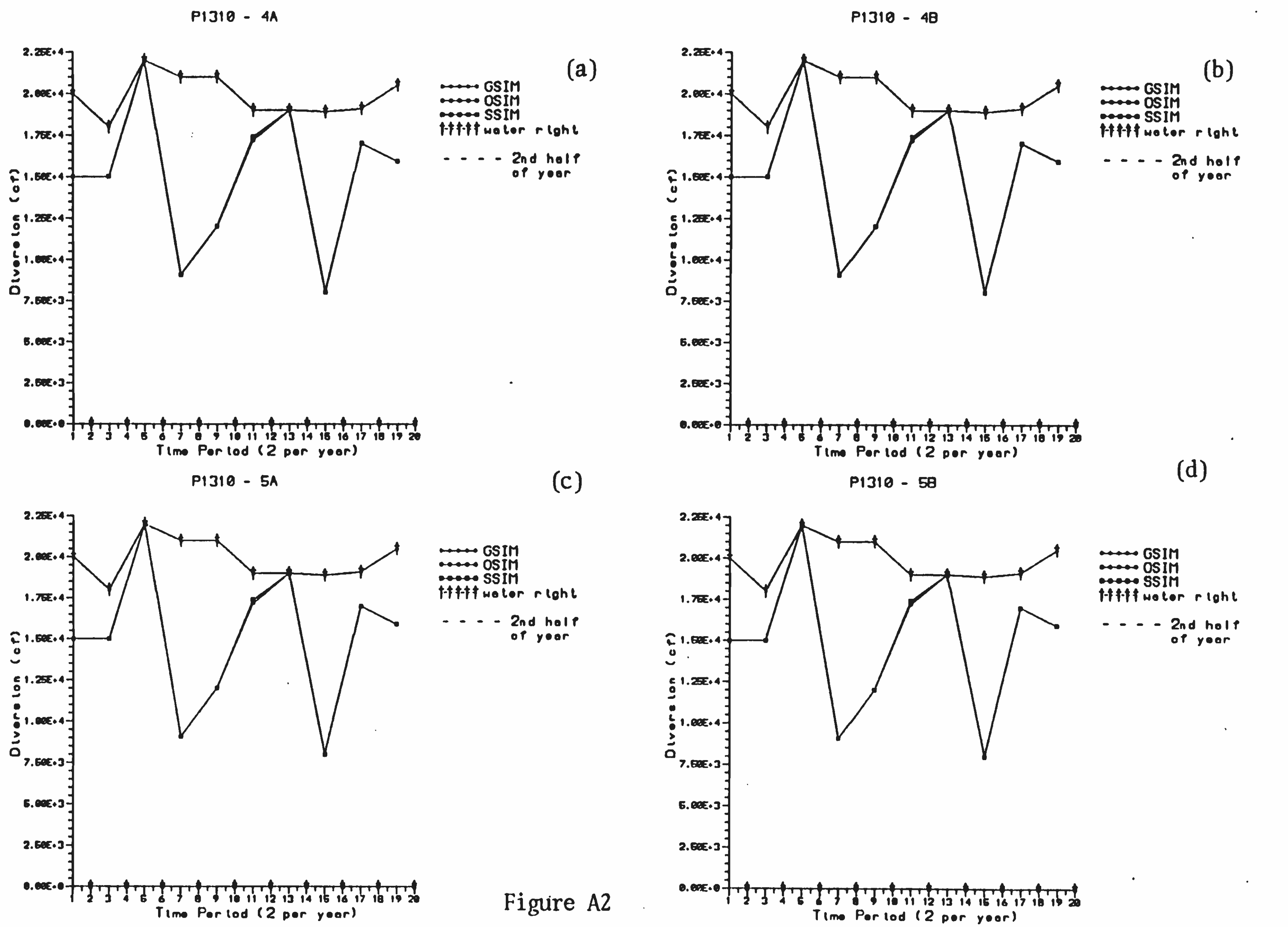
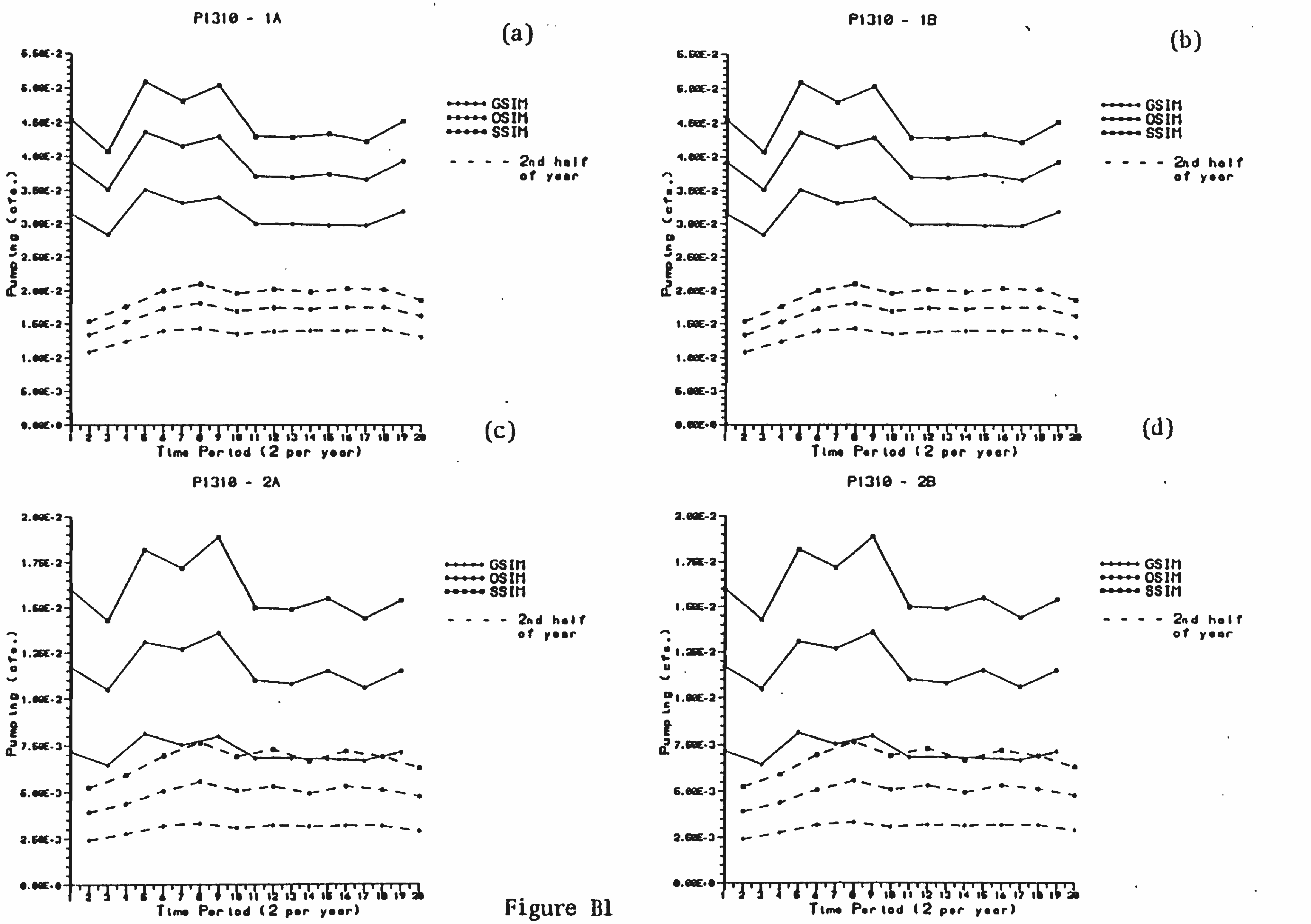

P1310 - 4A
(a)
GSIM
OSIM
SSIM
water right
2nd half of year
Diversion (cf)
Time Period (2 per year)
P1310 - 4B
(b)
P1310 - 5A
(c)
P1310 - 5B
(d)

Figure A2



P1310 - 1A
(a)
P1310 - 1B
(b)
(c)
P1310 - 2A
(d)
P1310 - 2B
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year

Figure B1

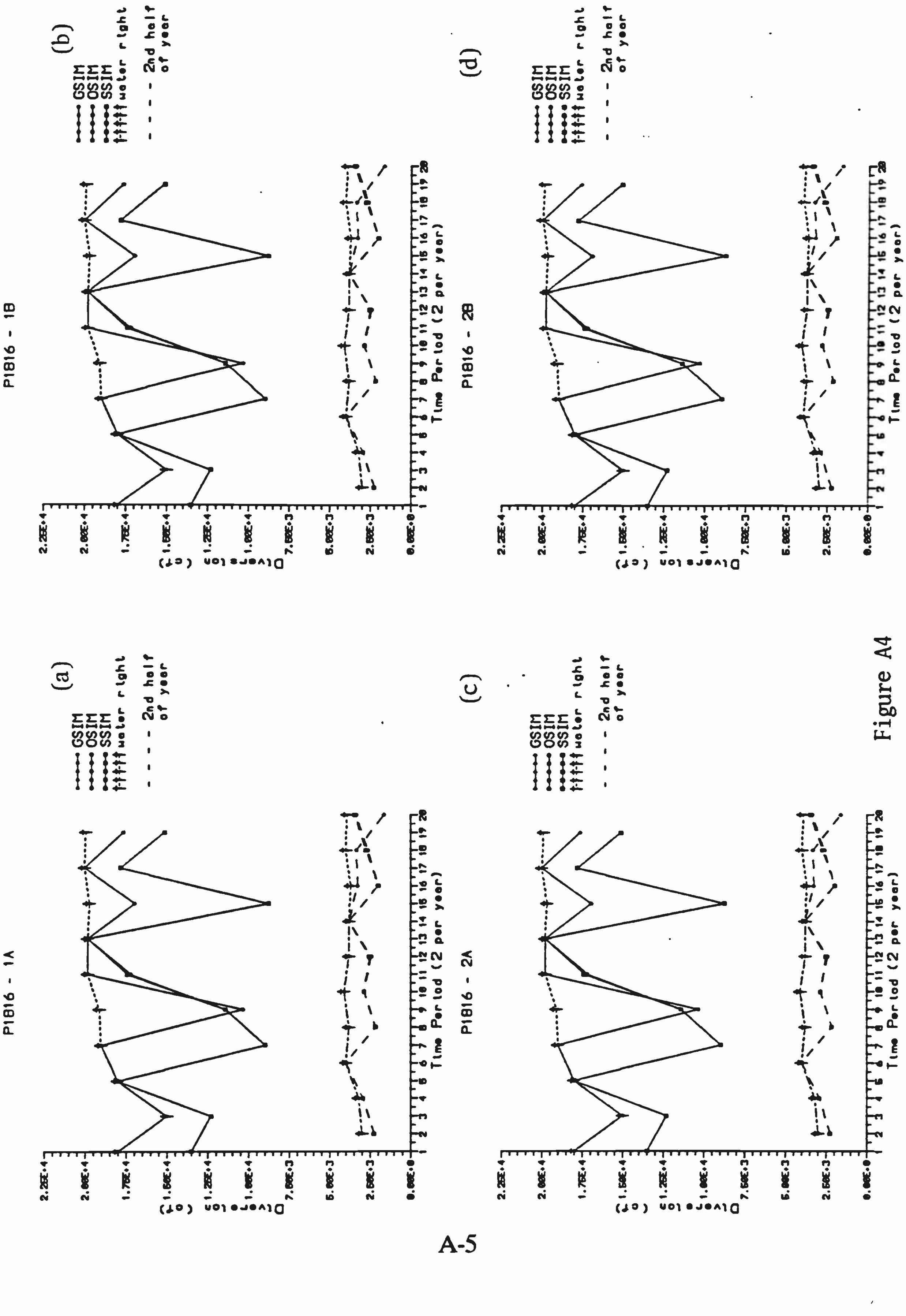
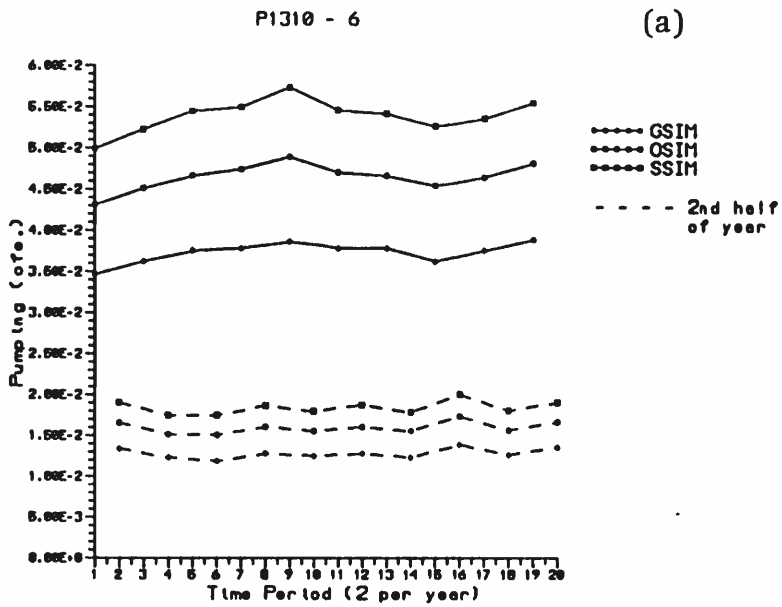
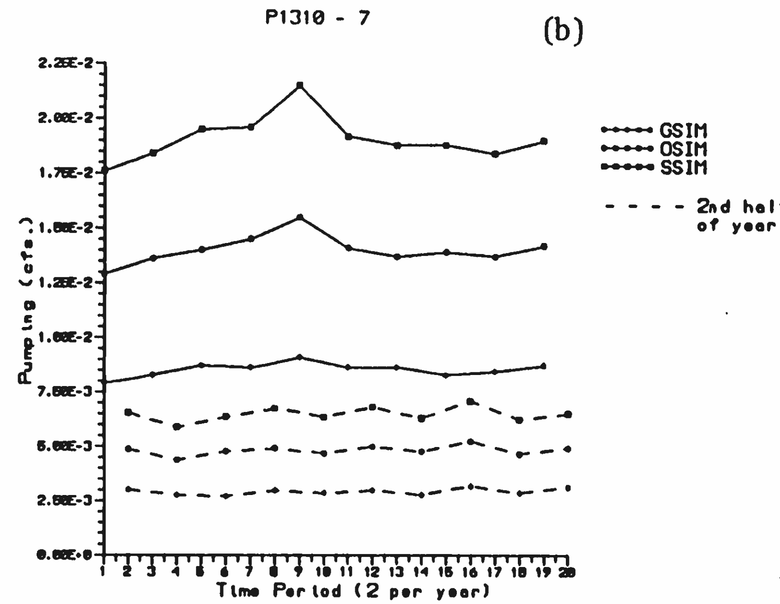

P1816 - 1A
P1816 - 1B
P1816 - 2A
P1816 - 2B
(a)
(b)
(c)
(d)
GSIM
OSIM
SSIM
water right
2nd half of year
Diversion (cf)
Time Period (2 per year)
2.25E+4
2.00E+4
1.75E+4
1.50E+4
1.25E+4
1.00E+4
7.50E+3
5.00E+3
2.50E+3
0.00E+0

Figure A4


P1310 - 6
(a)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year


P1310 - 7
(b)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year

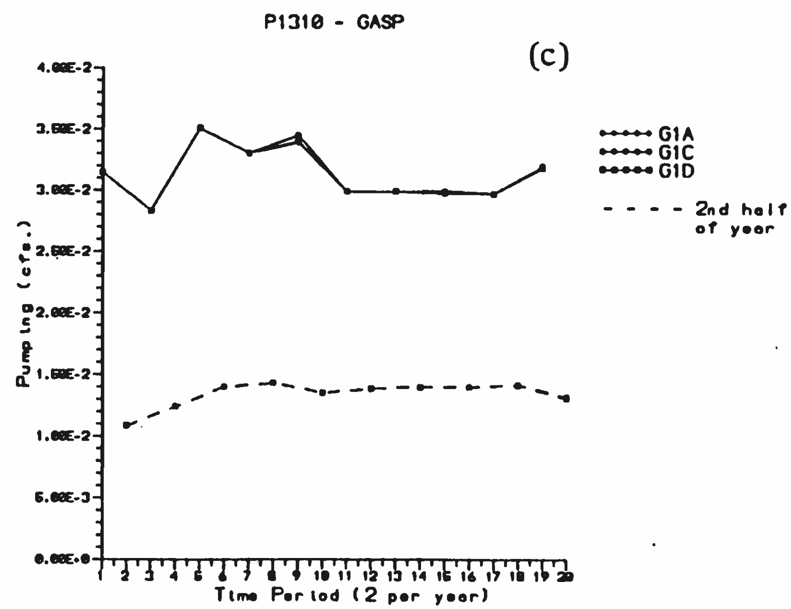
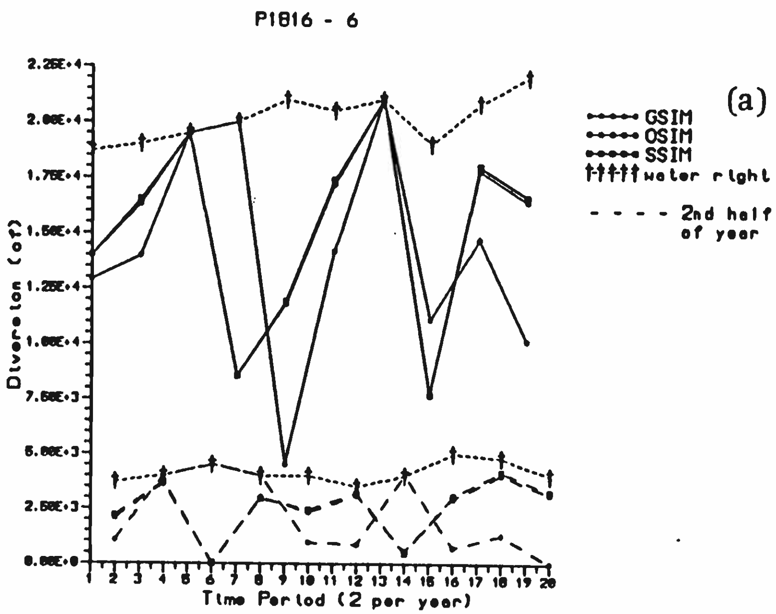
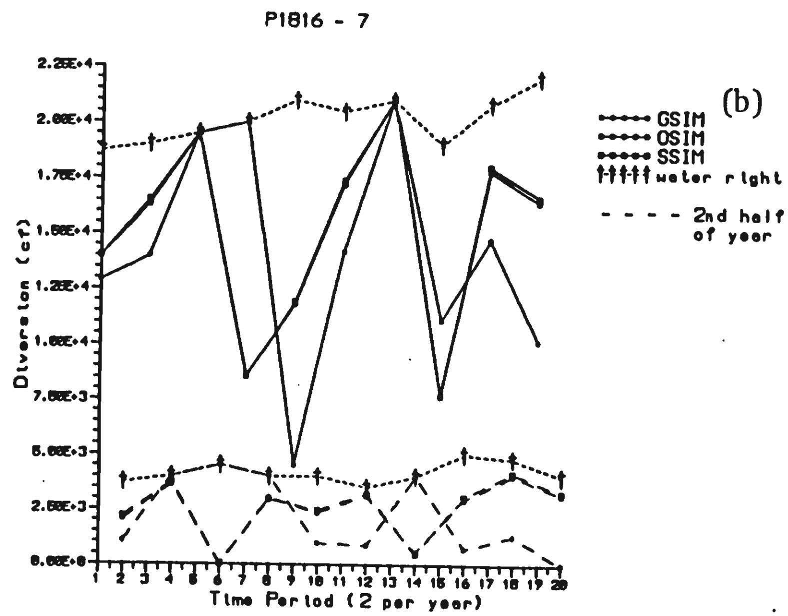

P1310 - GASP
(c)
Pumping (cfs.)
Time Period (2 per year)
G1A
G1C
G1D
2nd half of year

Figure B3


P1B16 - 6
(a)
Diversion (af)
2.25E+4
2.00E+4
1.75E+4
1.50E+4
1.25E+4
1.00E+4
7.50E+3
5.00E+3
2.50E+3
0.00E+0
Time Period (2 per year)
GSIM
OSIM
SSIM
water right
2nd half of year


P1B16 - 7
(b)
Diversion (af)
2.25E+4
2.00E+4
1.75E+4
1.50E+4
1.25E+4
1.00E+4
7.50E+3
5.00E+3
2.50E+3
0.00E+0
Time Period (2 per year)
GSIM
OSIM
SSIM
water right
2nd half of year

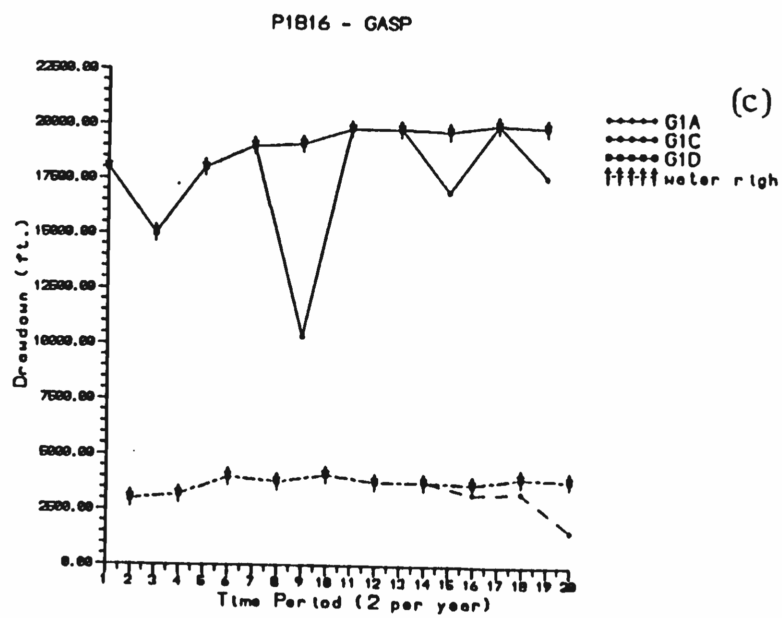

P1B16 - GASP
(c)
Drawdown (ft.)
22500.00
20000.00
17500.00
15000.00
12500.00
10000.00
7500.00
5000.00
2500.00
0.00
Time Period (2 per year)
G1A
G1C
G1D
water right

Figure A6

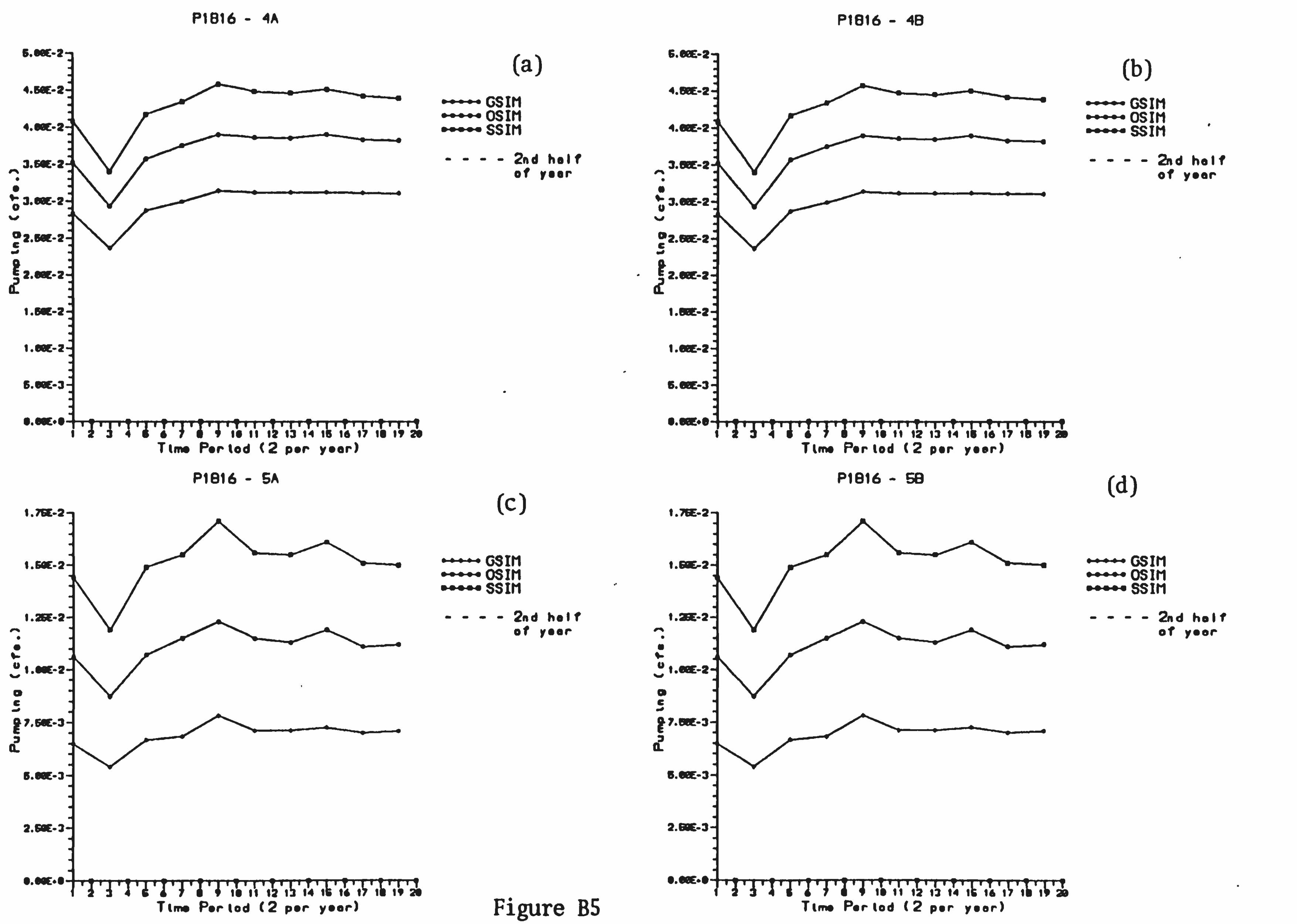
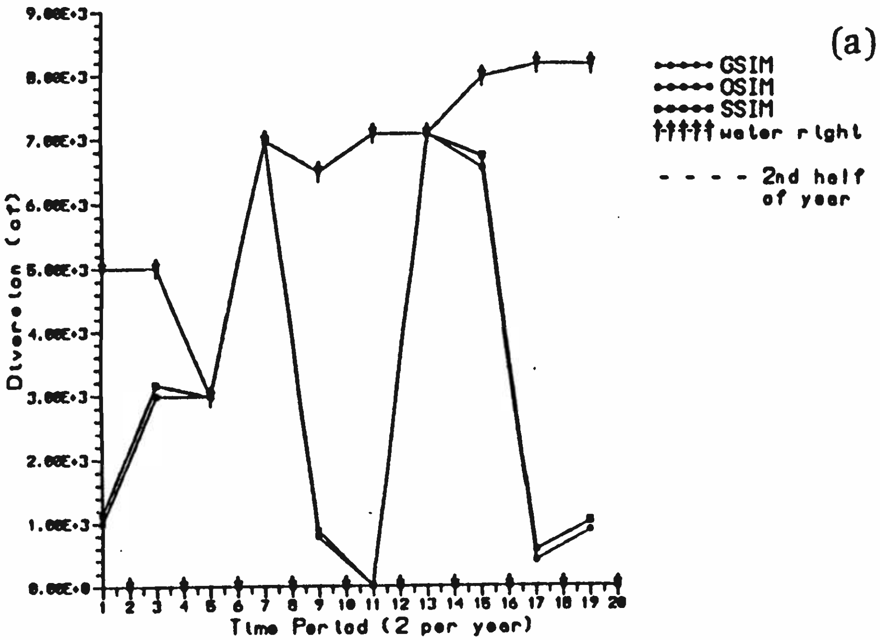
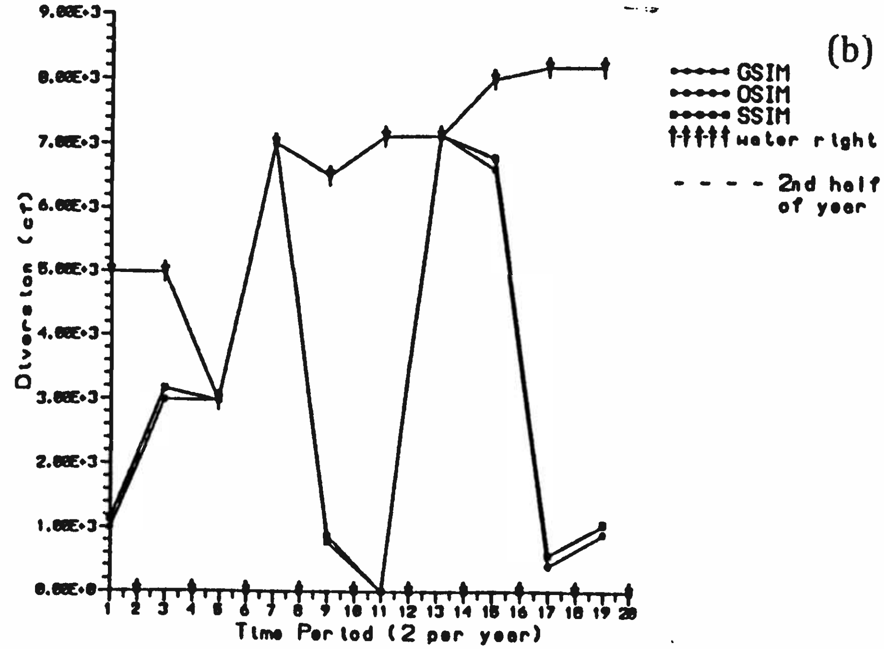

P1816 - 4A
(a)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year
P1816 - 4B
(b)
P1816 - 5A
(c)
P1816 - 5B
(d)

Figure B5

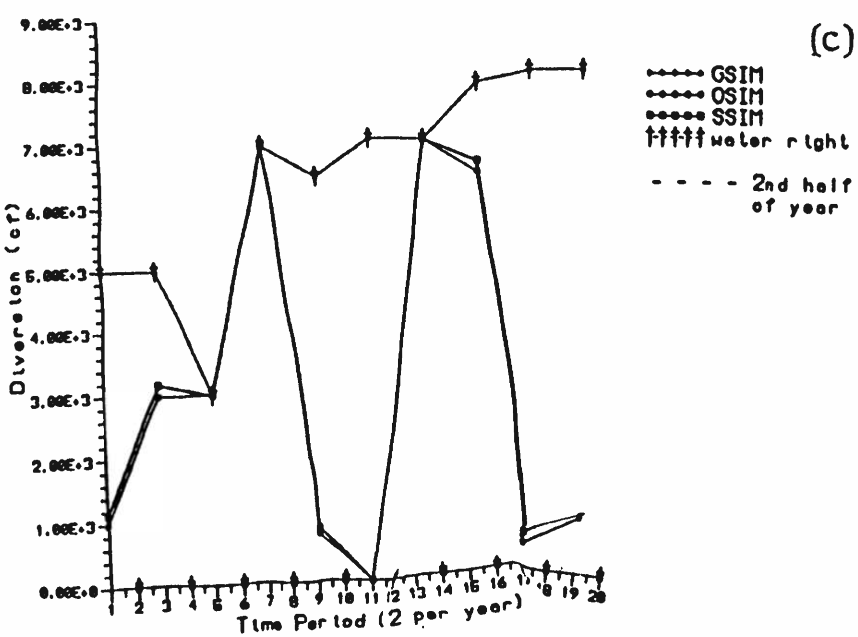
P236 - 4A



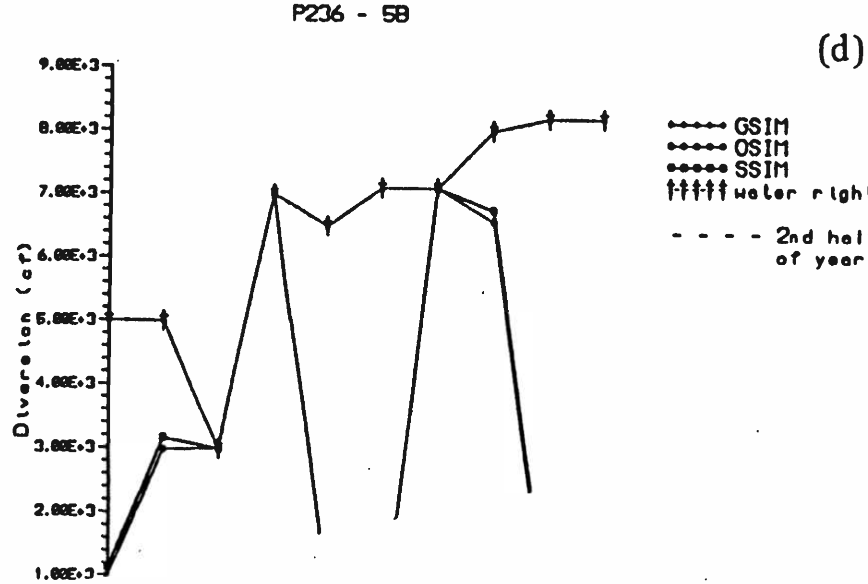
P236

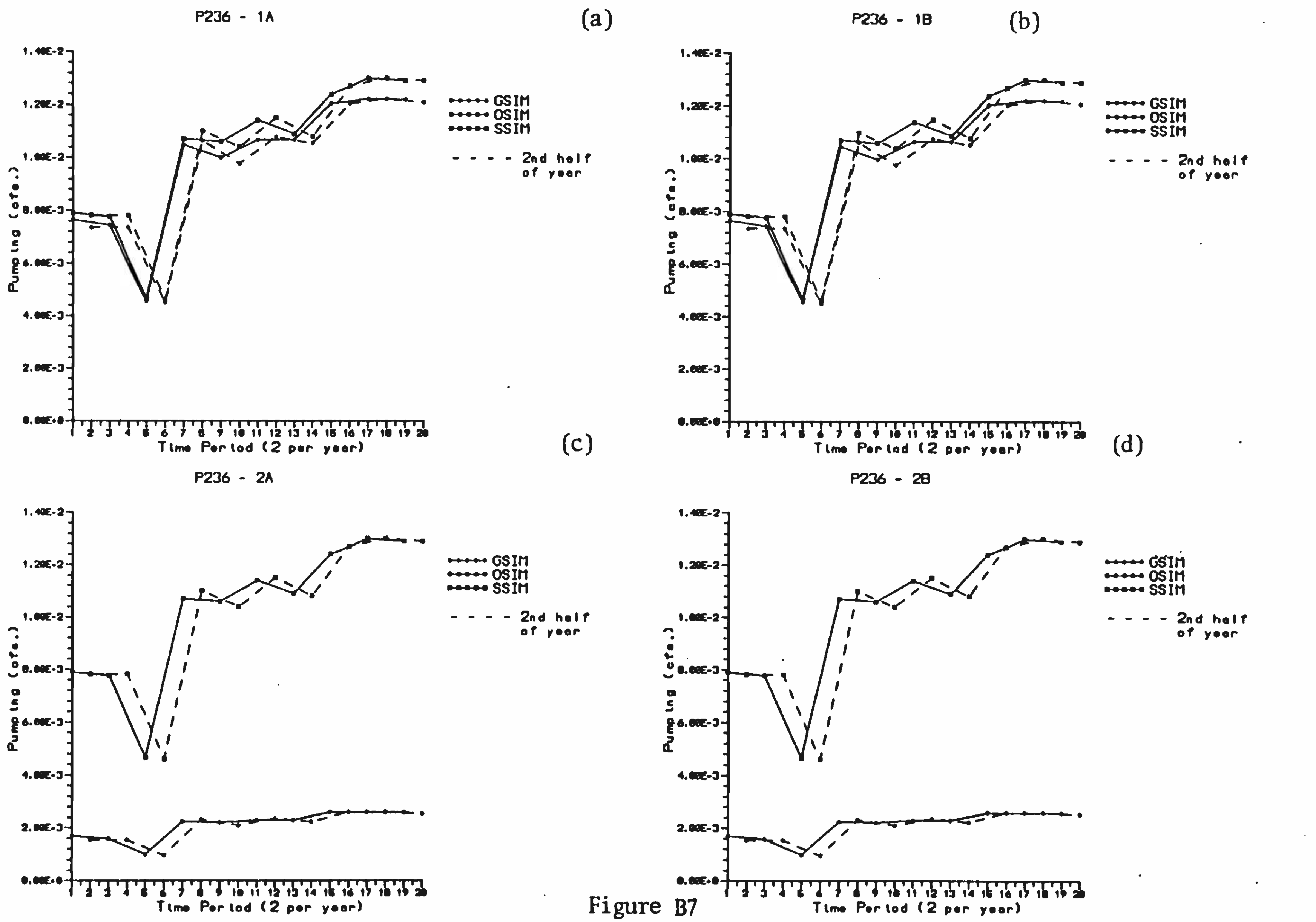


P236 - 5A



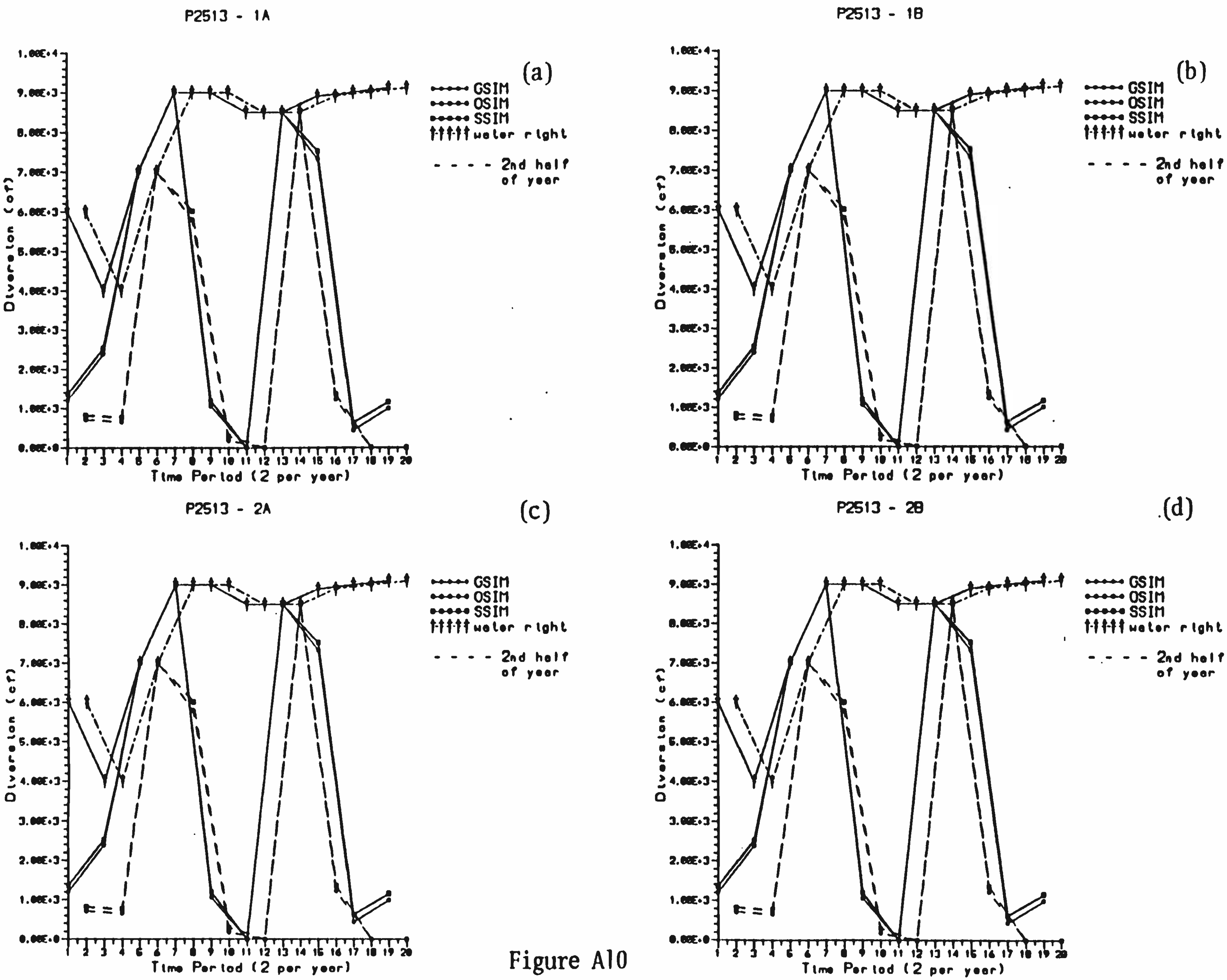
P236 - 5B





P236 - 1A
(a)
P236 - 1B
(b)
P236 - 2A
(c)
P236 - 2B
(d)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year
1.40E-2
1.20E-2
1.00E-2
8.00E-3
6.00E-3
4.00E-3
2.00E-3
0.00E+0

Figure B7



P2513 - 1A
(a)
P2513 - 1B
(b)
P2513 - 2A
(c)
P2513 - 2B
(d)
GSIM
OSIM
SSIM
water right
2nd half of year
Diversion (cf)
Time Period (2 per year)
1.00E+4
9.00E+3
8.00E+3
7.00E+3
6.00E+3
5.00E+3
4.00E+3
3.00E+3
2.00E+3
1.00E+3
0.00E+0

Figure A10

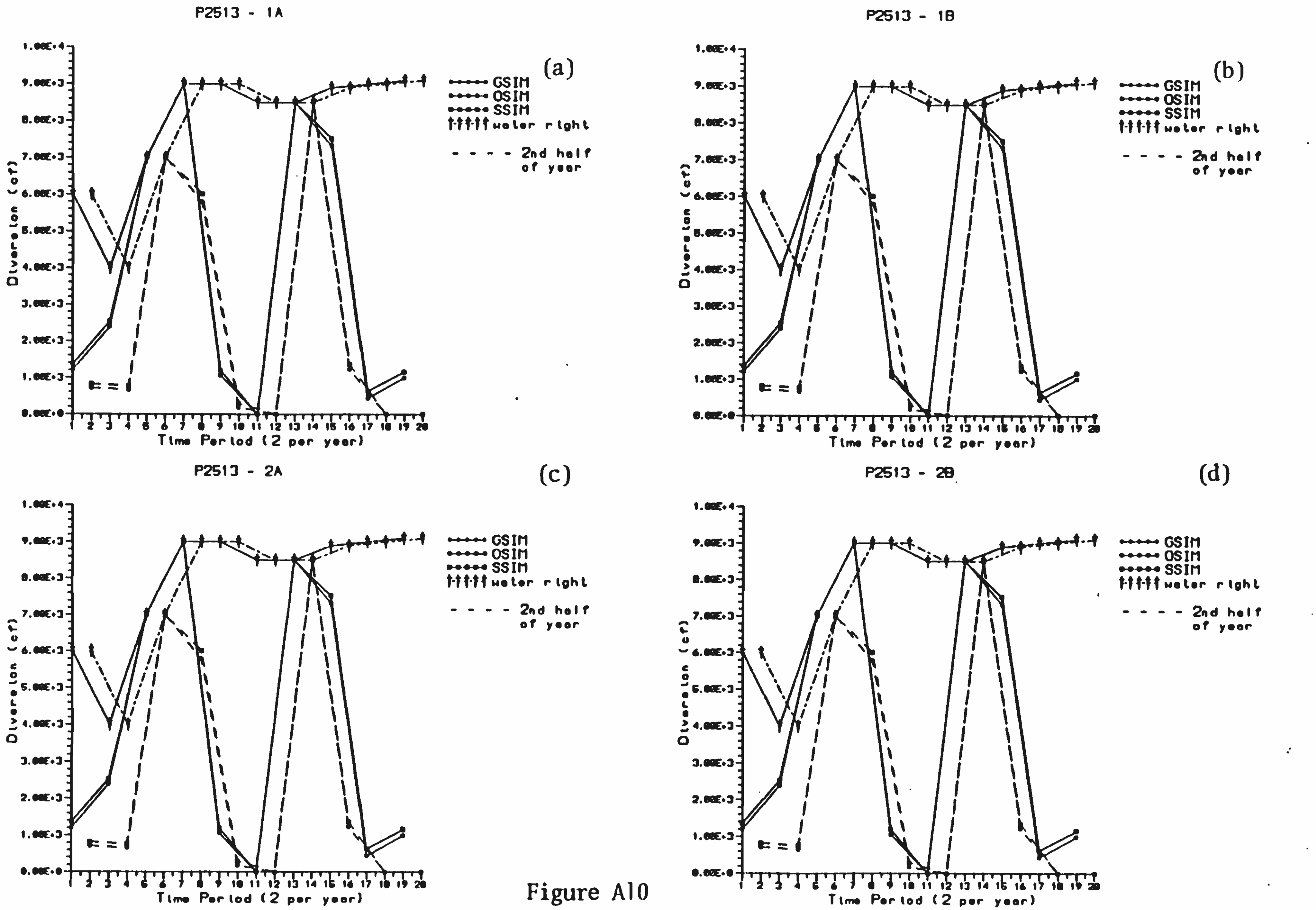

P2513 - 1A
(a)
P2513 - 1B
(b)
P2513 - 2A
(c)
P2513 - 2B
(d)
Diversion (cf)
Time Period (2 per year)
GSIM
OSIM
SSIM
water right
2nd half of year

Figure A10

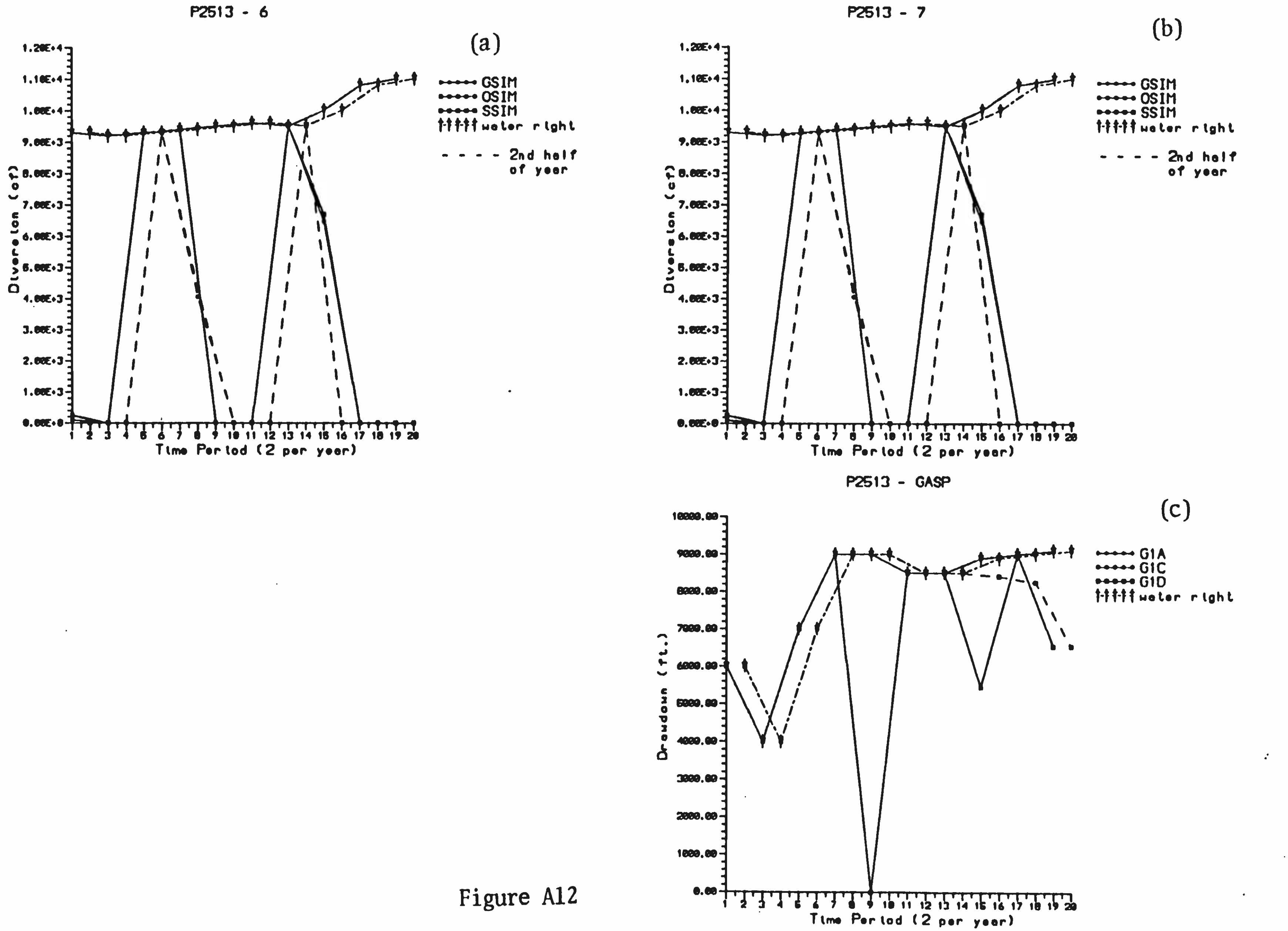

P2513 - 6
(a)
Diversion (af)
Time Period (2 per year)
GSIM
OSIM
SSIM
water right
2nd half of year
P2513 - 7
(b)
Diversion (af)
Time Period (2 per year)
GSIM
OSIM
SSIM
water right
2nd half of year
P2513 - GASP
(c)
Drawdown (ft.)
Time Period (2 per year)
G1A
G1C
G1D
water right

Figure A12

APPENDIX B

Pumping Plots

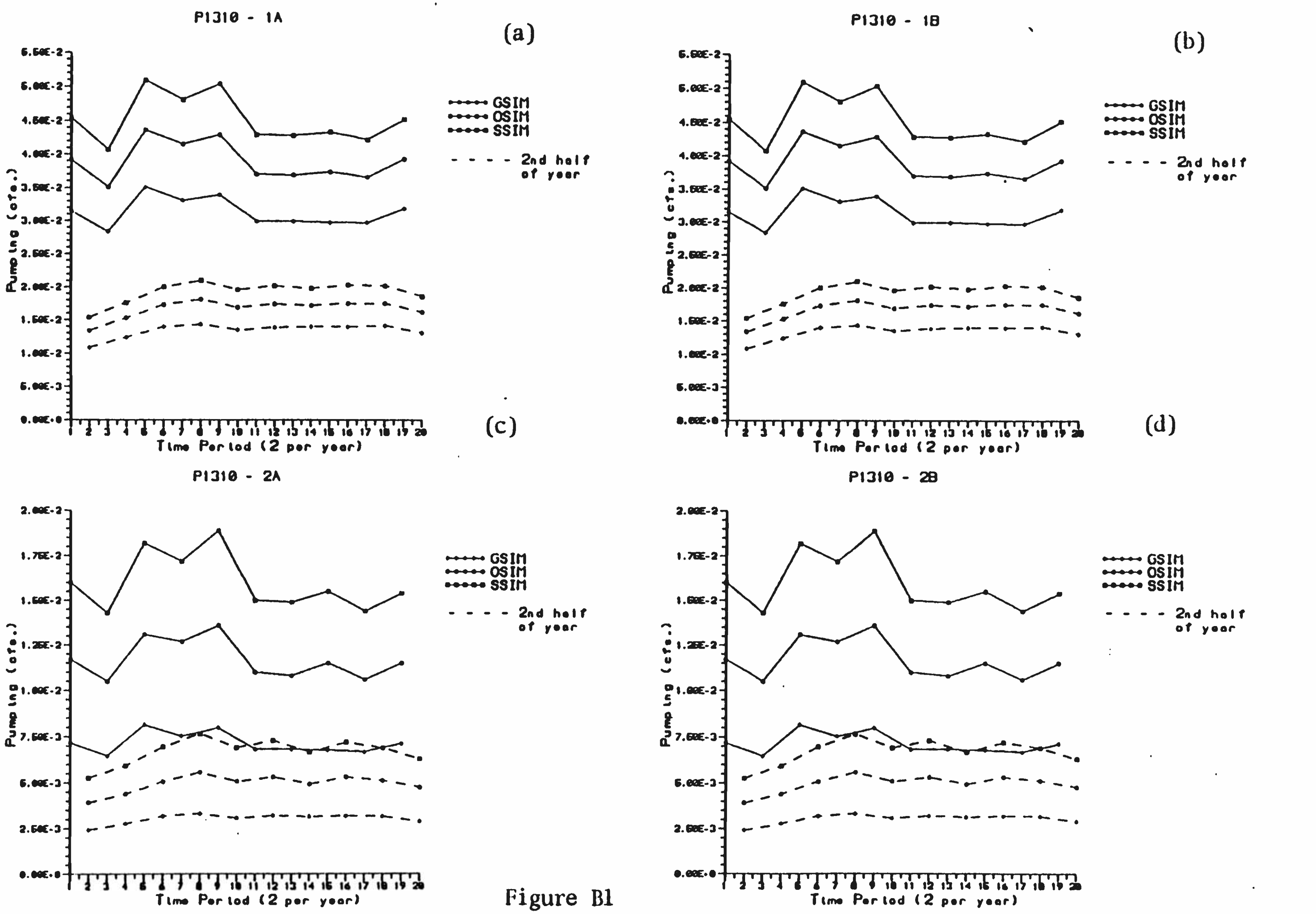

P1310 - 1A
(a)
P1310 - 1B
(b)
(c)
P1310 - 2A
(d)
P1310 - 2B
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)

Figure B1

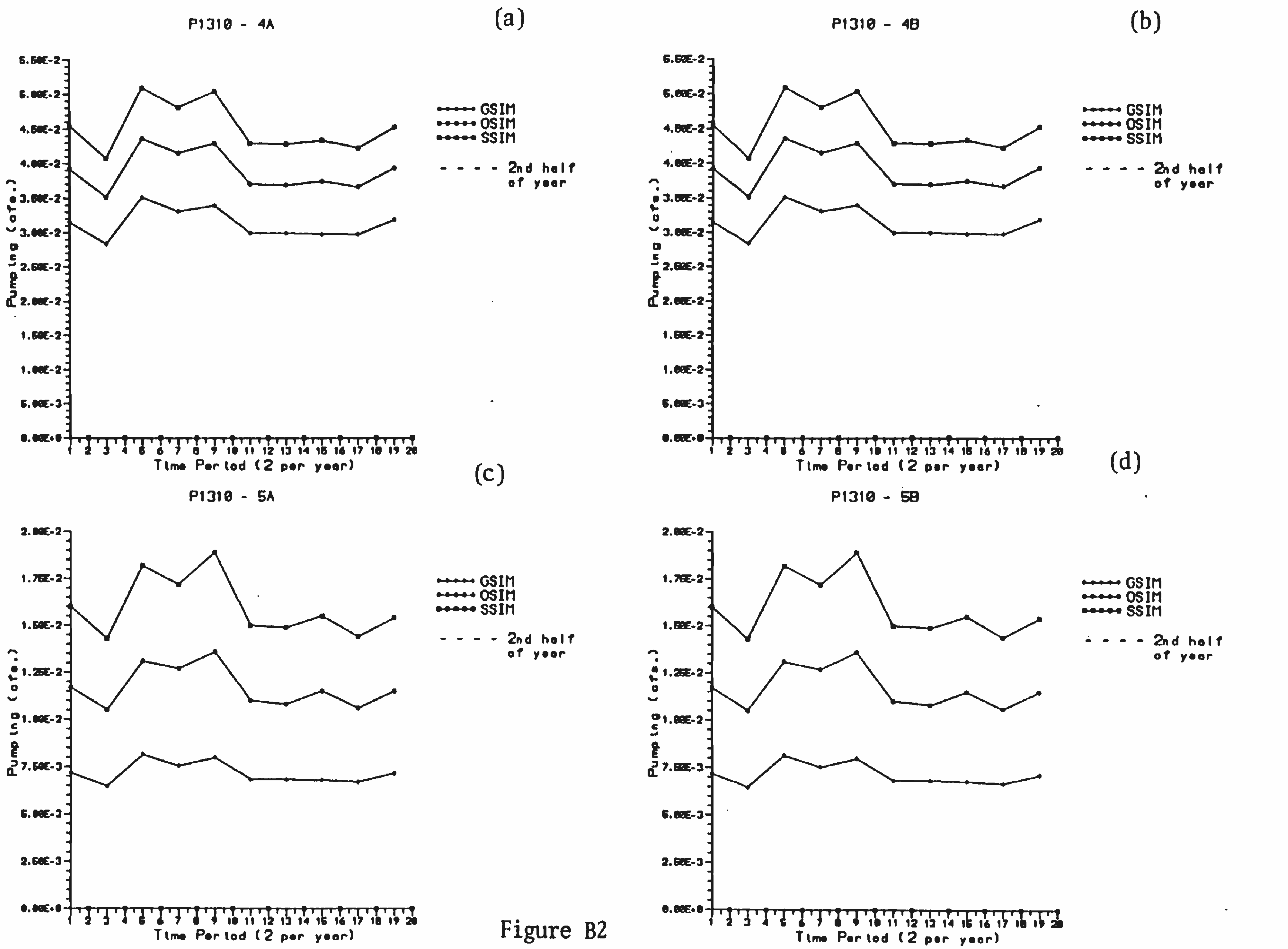
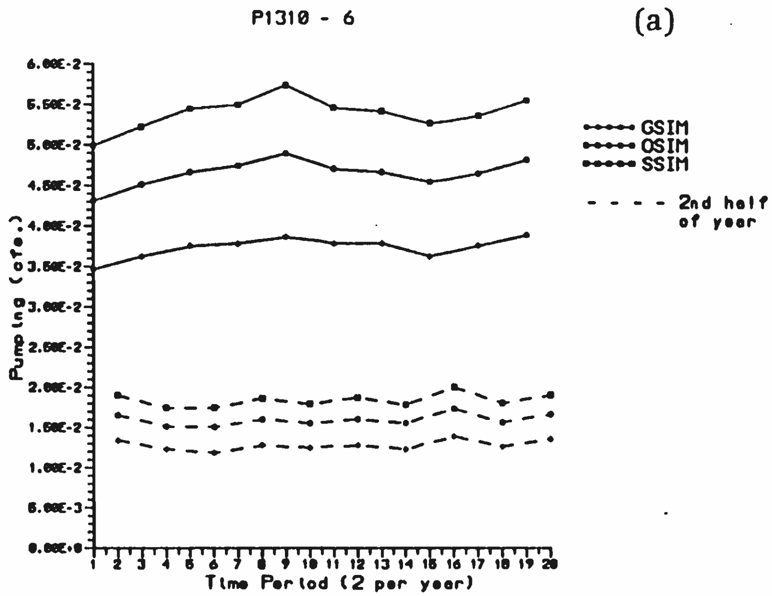
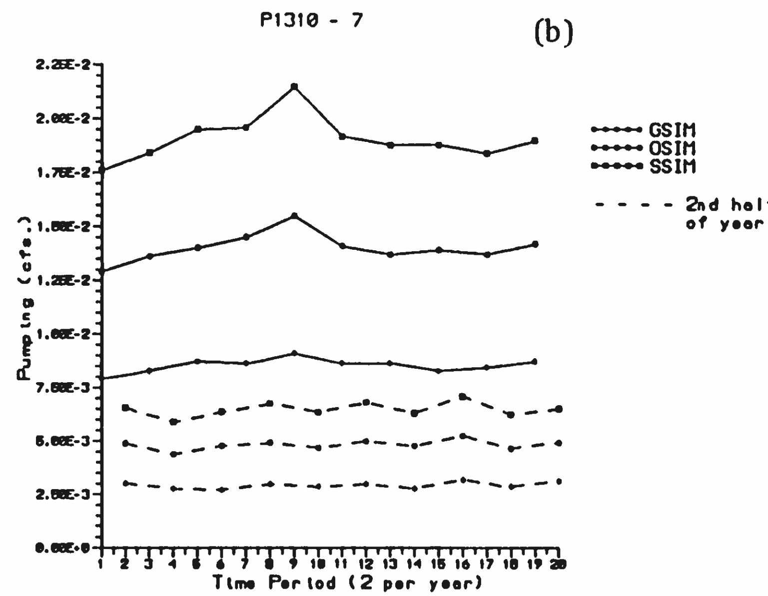

(a)
P1310 - 4A
(b)
P1310 - 4B
(c)
P1310 - 5A
(d)
P1310 - 5B
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)

Figure B2


P1310 - 6
(a)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year


P1310 - 7
(b)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year

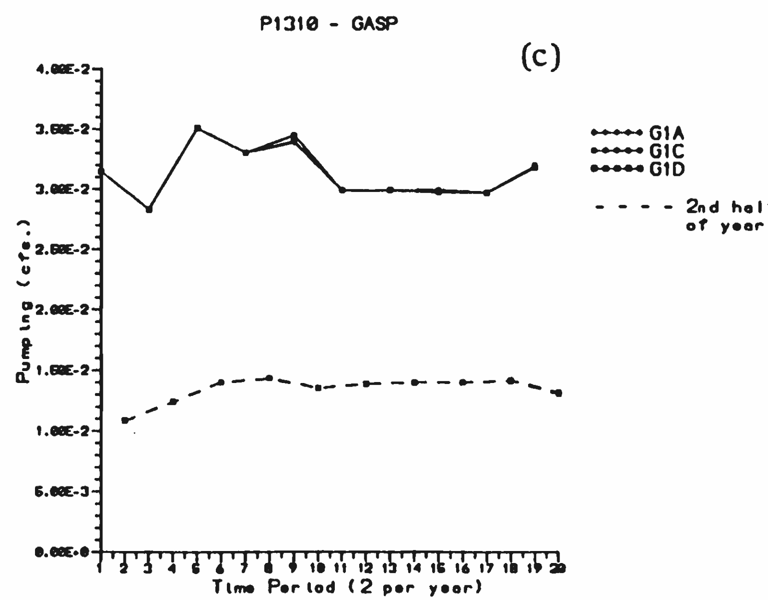

P1310 - GASP
(c)
Pumping (cfs.)
Time Period (2 per year)
G1A
G1C
G1D
2nd half of year

Figure B3

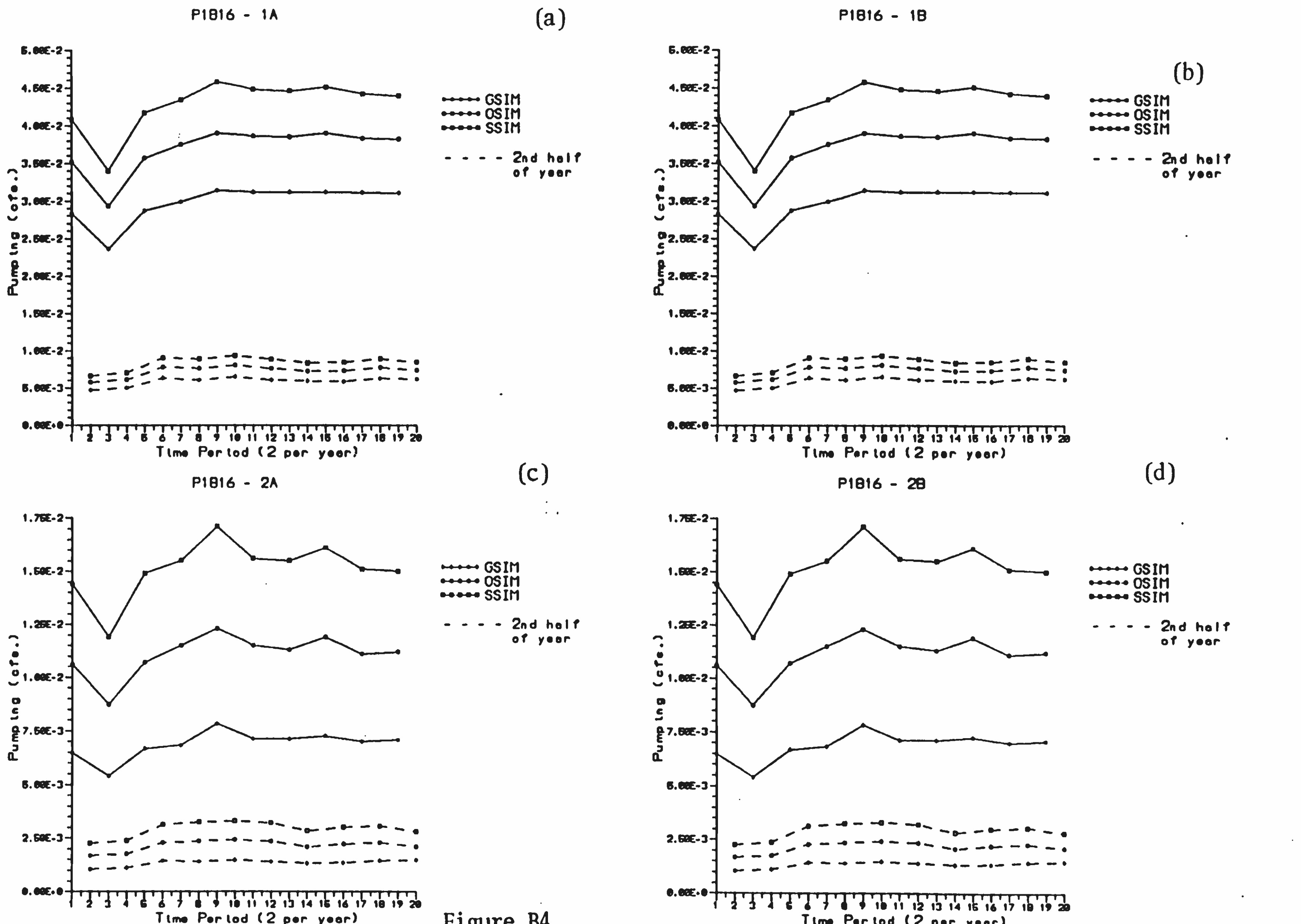
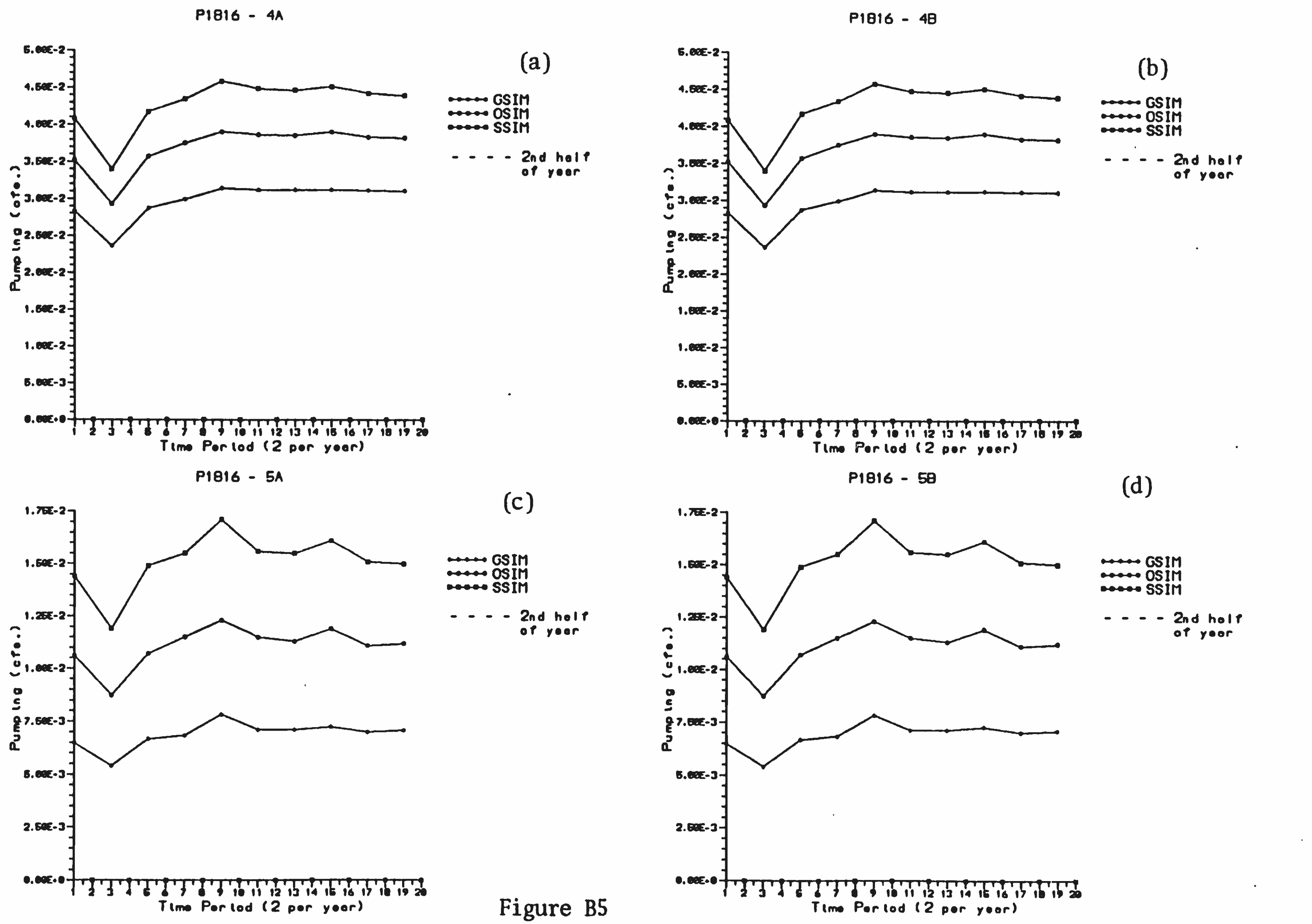

P1B16 - 1A
(a)
P1B16 - 1B
(b)
P1B16 - 2A
(c)
P1B16 - 2B
(d)
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)

Figure B4



P1816 - 4A
(a)
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)
P1816 - 4B
(b)
P1816 - 5A
(c)
P1816 - 5B
(d)

Figure B5

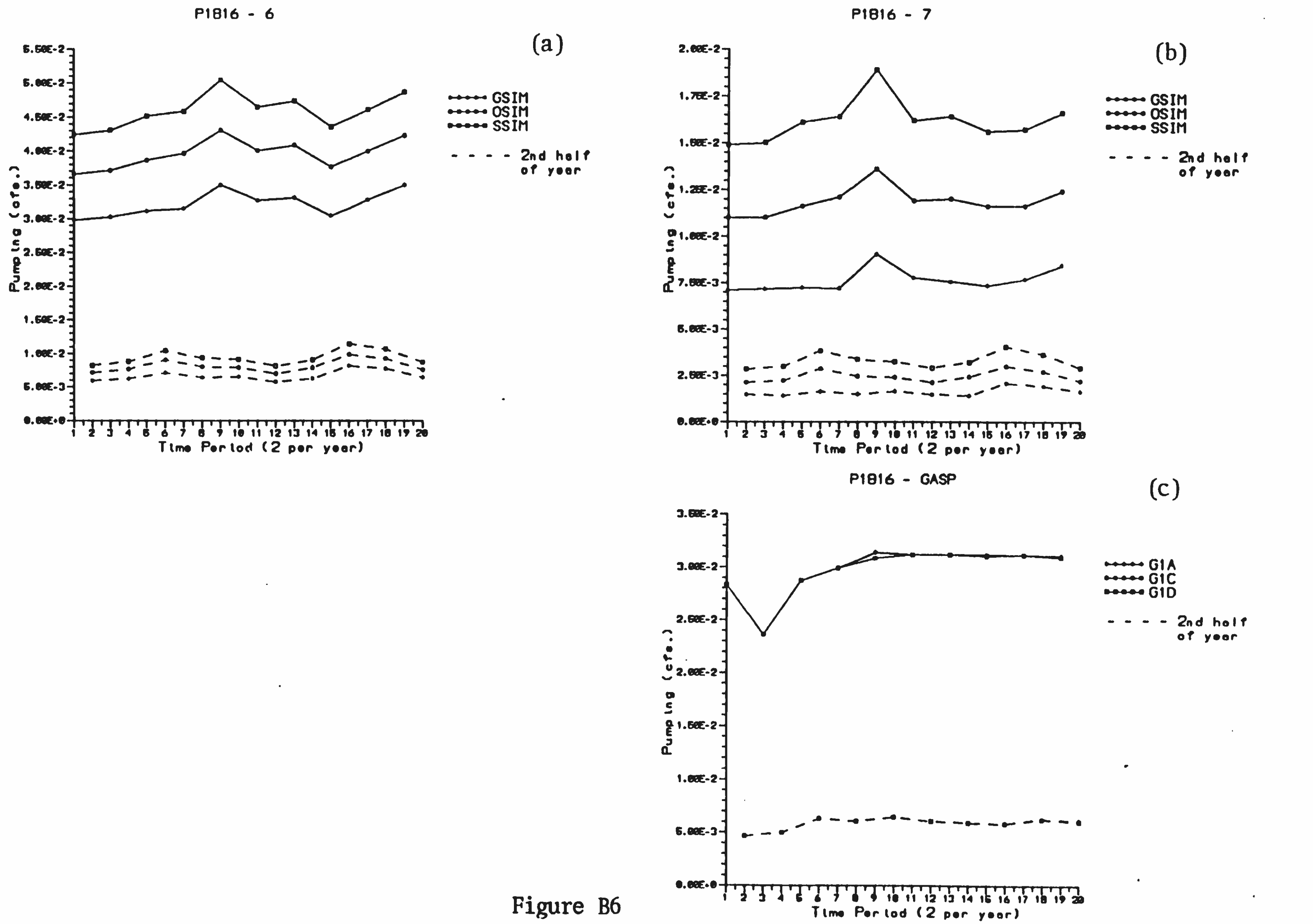

P1B16 - 6
(a)
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)
P1B16 - 7
(b)
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)
P1B16 - GASP
(c)
G1A
G1C
G1D
2nd half of year
Pumping (cfs.)
Time Period (2 per year)

Figure B6

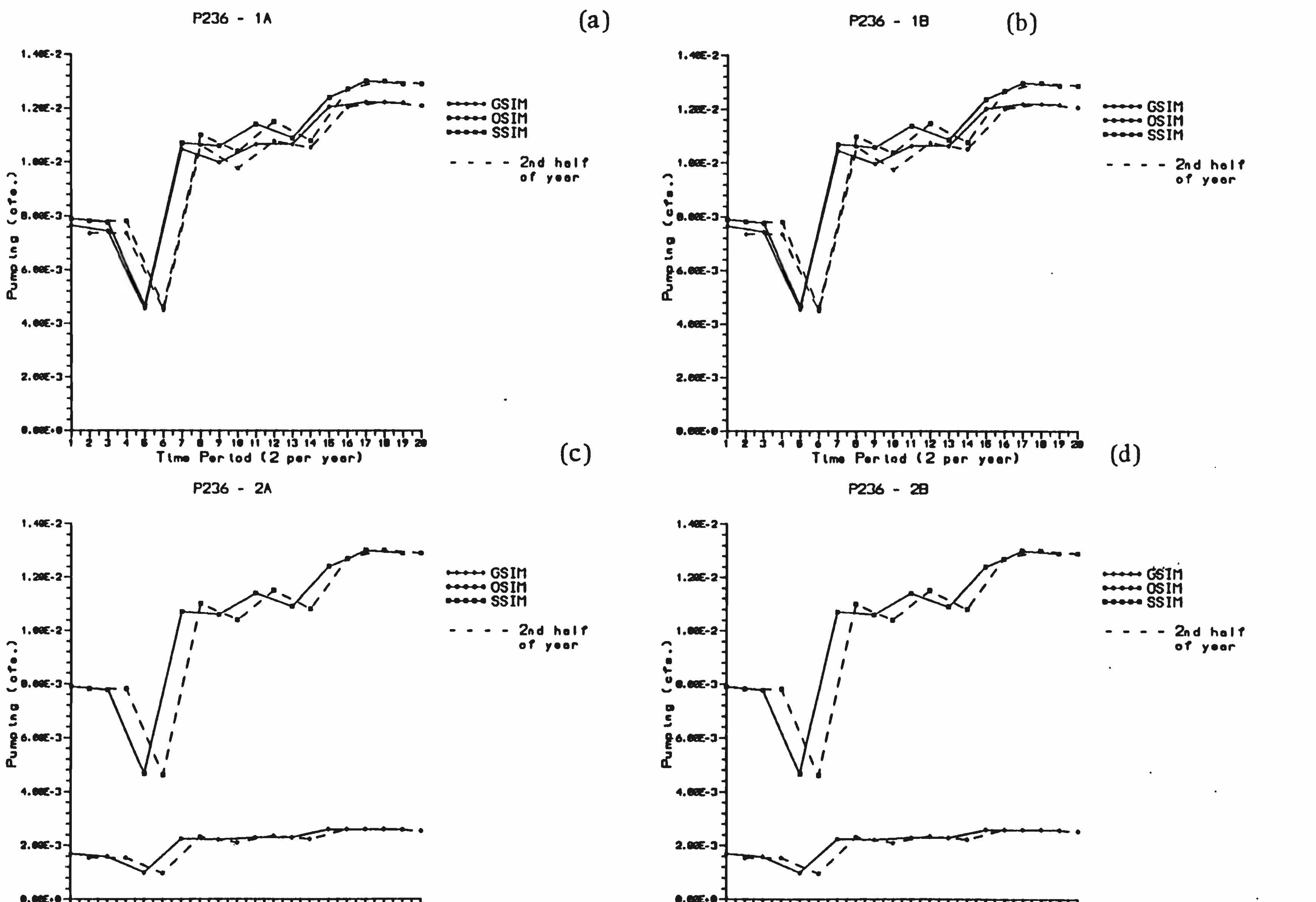

P236 - 1A
(a)
P236 - 1B
(b)
(c)
P236 - 2A
(d)
P236 - 2B
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year
1.40E-2
1.20E-2
1.00E-2
8.00E-3
6.00E-3
4.00E-3
2.00E-3
0.00E+0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure B7

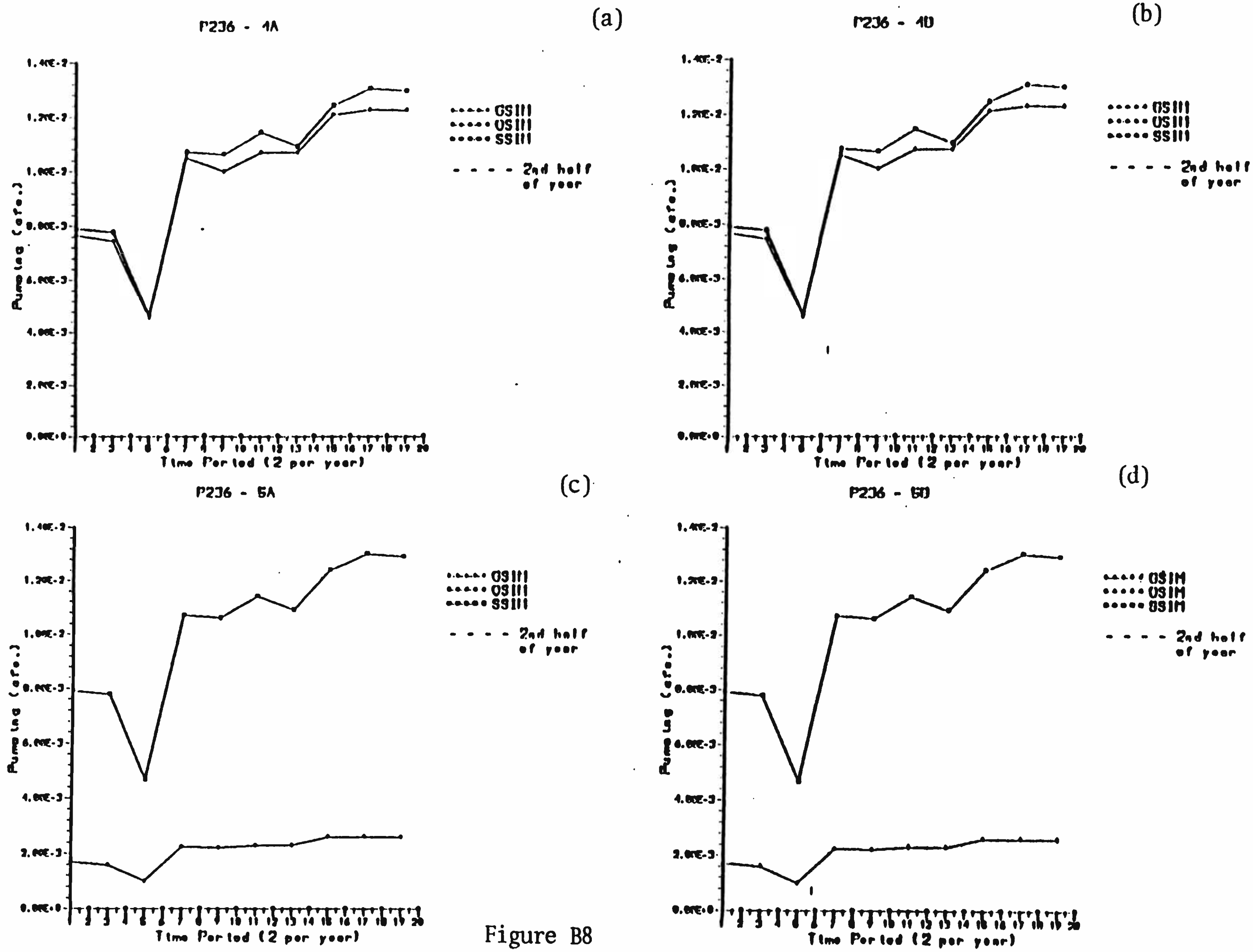
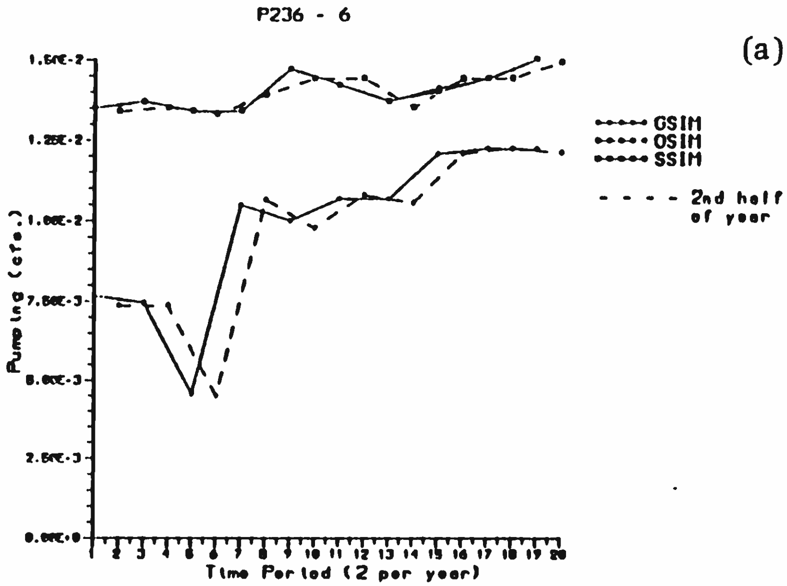
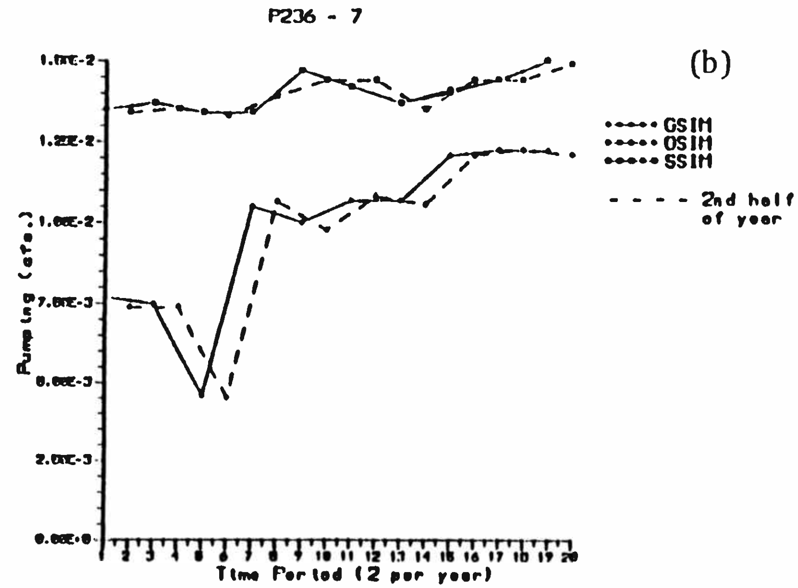

(a)
P236 - 4A
(b)
P236 - 4D
(c)
P236 - 5A
(d)
P236 - 5D
Pumping (afe.)
Time Period (2 per year)
OSIII
USIII
SSIII
2nd half of year
OSIM
USIM
SSIM

Figure B8


P236 - 6
(a)
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)


P236 - 7
(b)
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)

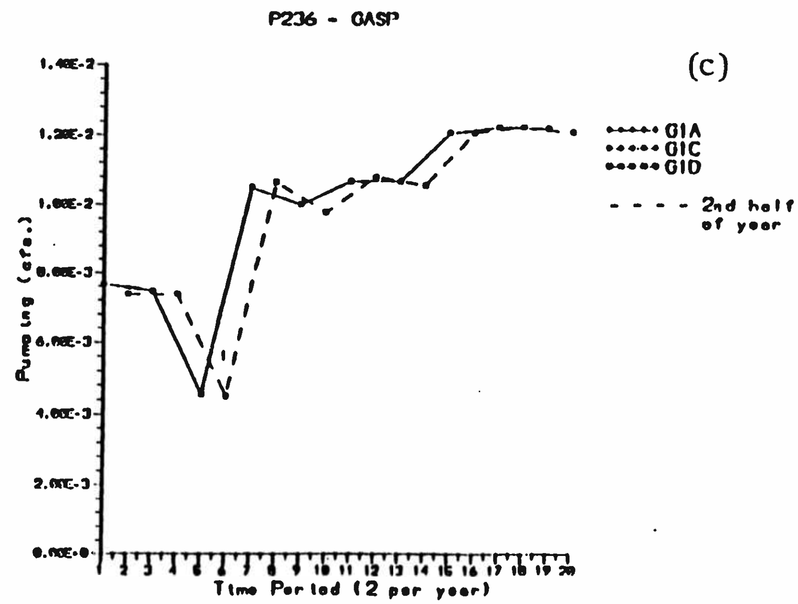

P236 - GASP
(c)
GIA
GIC
GID
2nd half of year
Pumping (cfs.)
Time Period (2 per year)

Figure B9

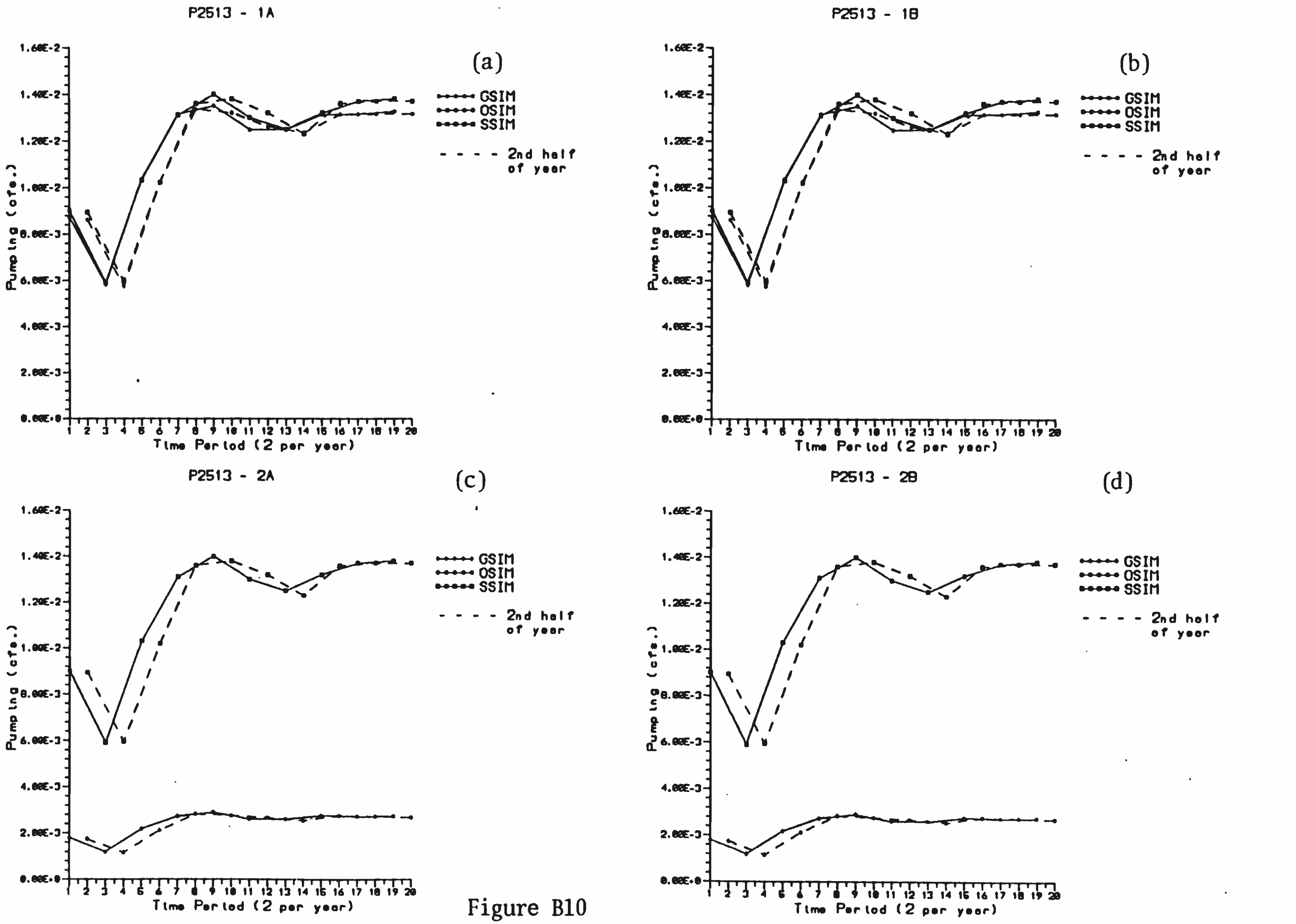

P2513 - 1A
(a)
P2513 - 1B
(b)
P2513 - 2A
(c)
P2513 - 2B
(d)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year
1.60E-2
1.40E-2
1.20E-2
1.00E-2
8.00E-3
6.00E-3
4.00E-3
2.00E-3
0.00E+0

Figure B10

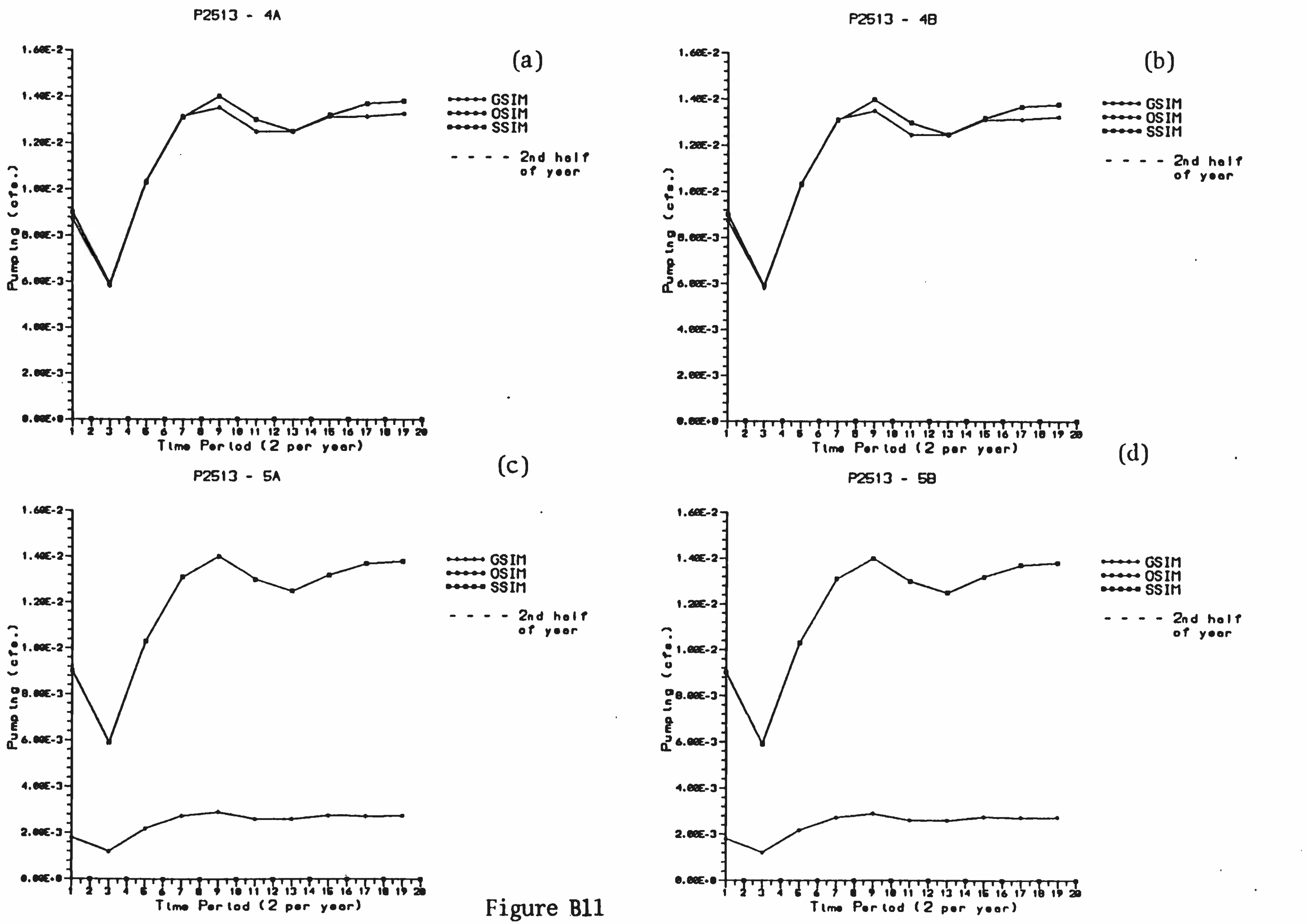
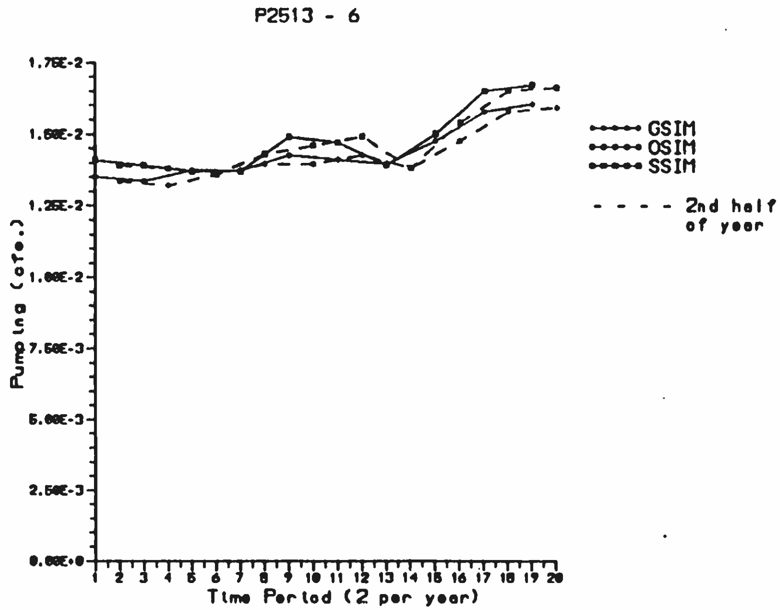
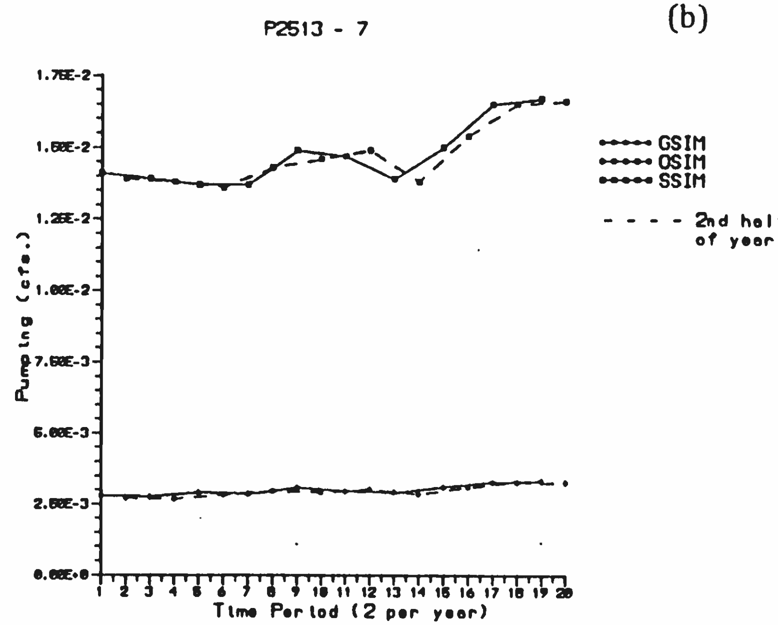

P2513 - 4A
(a)
GSIM
OSIM
SSIM
- - - - 2nd half of year
Pumping (cfs.)
Time Period (2 per year)
P2513 - 4B
(b)
P2513 - 5A
(c)
P2513 - 5B
(d)

Figure B11

(a)



(b)



(c)

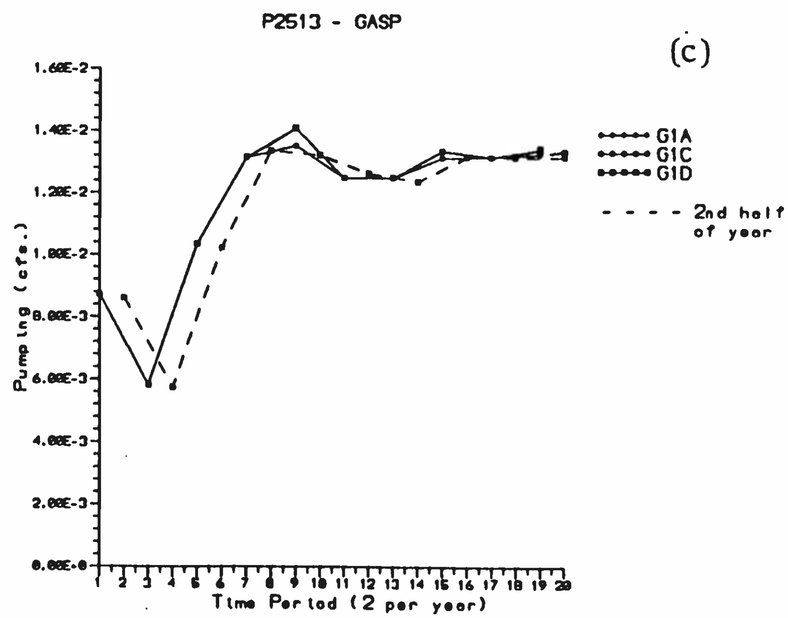
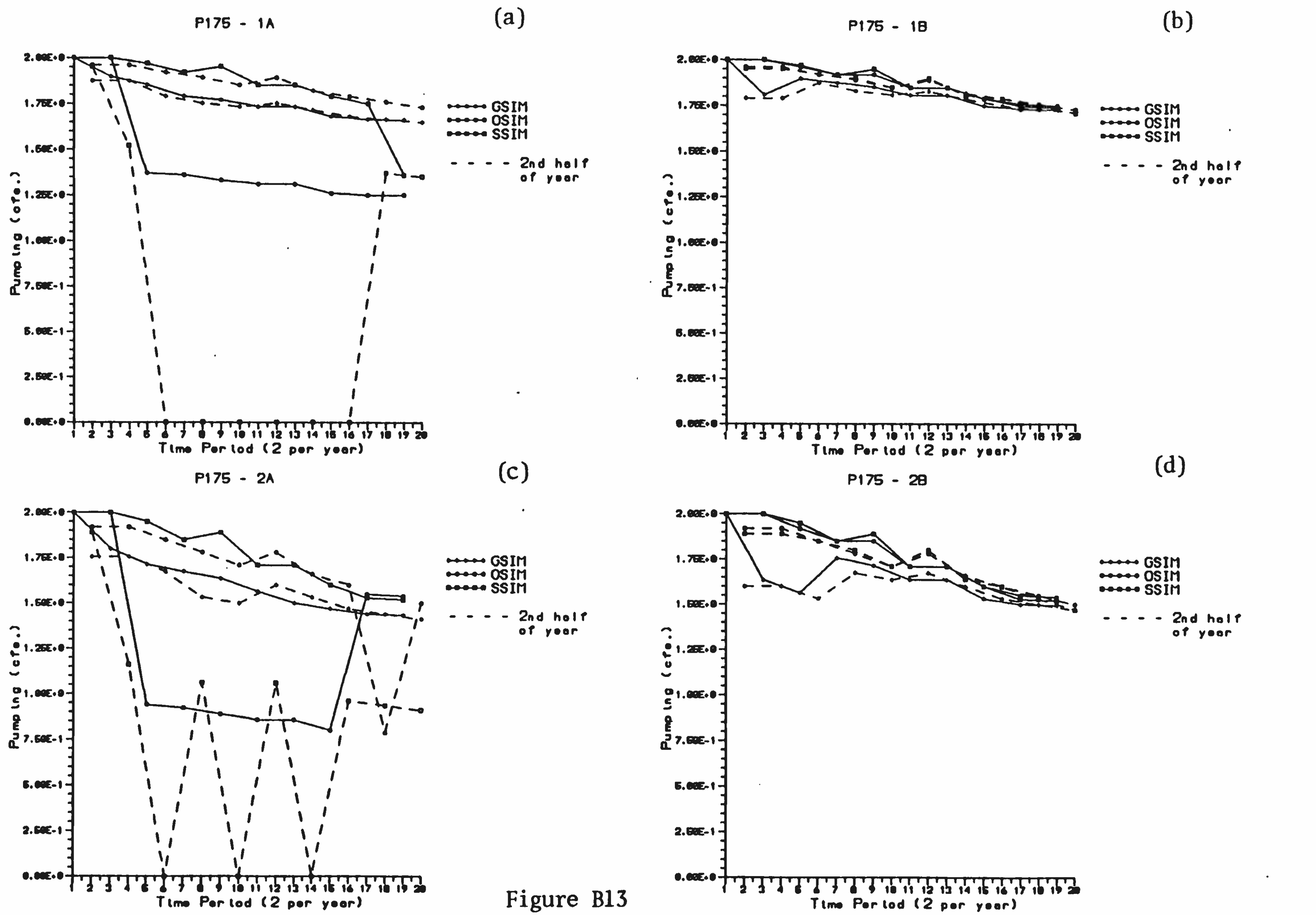


Figure B12



P175 - 1A
(a)
2.00E+0
1.75E+0
1.50E+0
1.25E+0
1.00E+0
7.50E-1
5.00E-1
2.50E-1
0.00E+0
Pumping (cfs.)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year
P175 - 1B
(b)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year
P175 - 2A
(c)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year
P175 - 2B
(d)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year

Figure B13

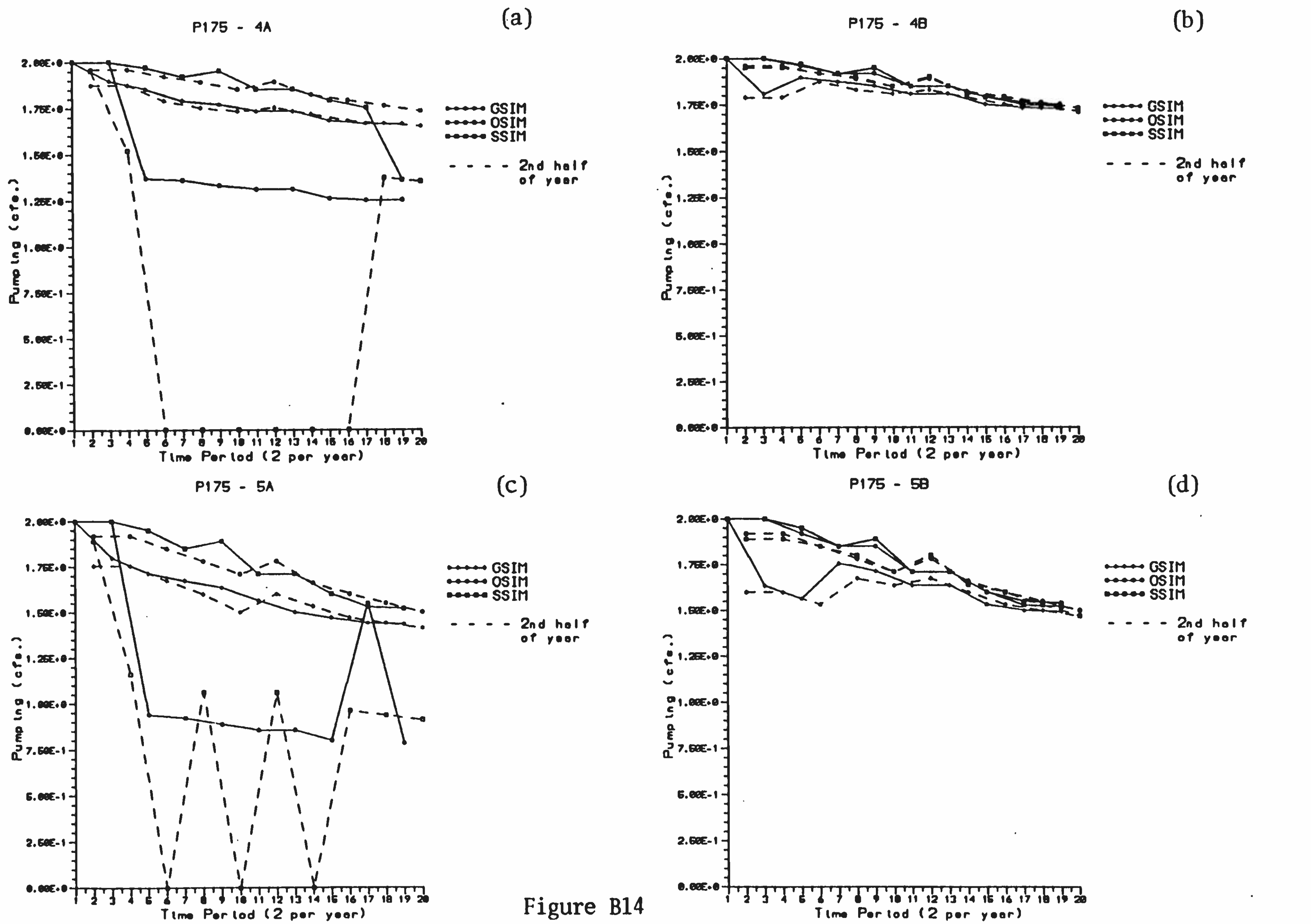

P175 - 4A
(a)
P175 - 4B
(b)
P175 - 5A
(c)
P175 - 5B
(d)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year

Figure B14

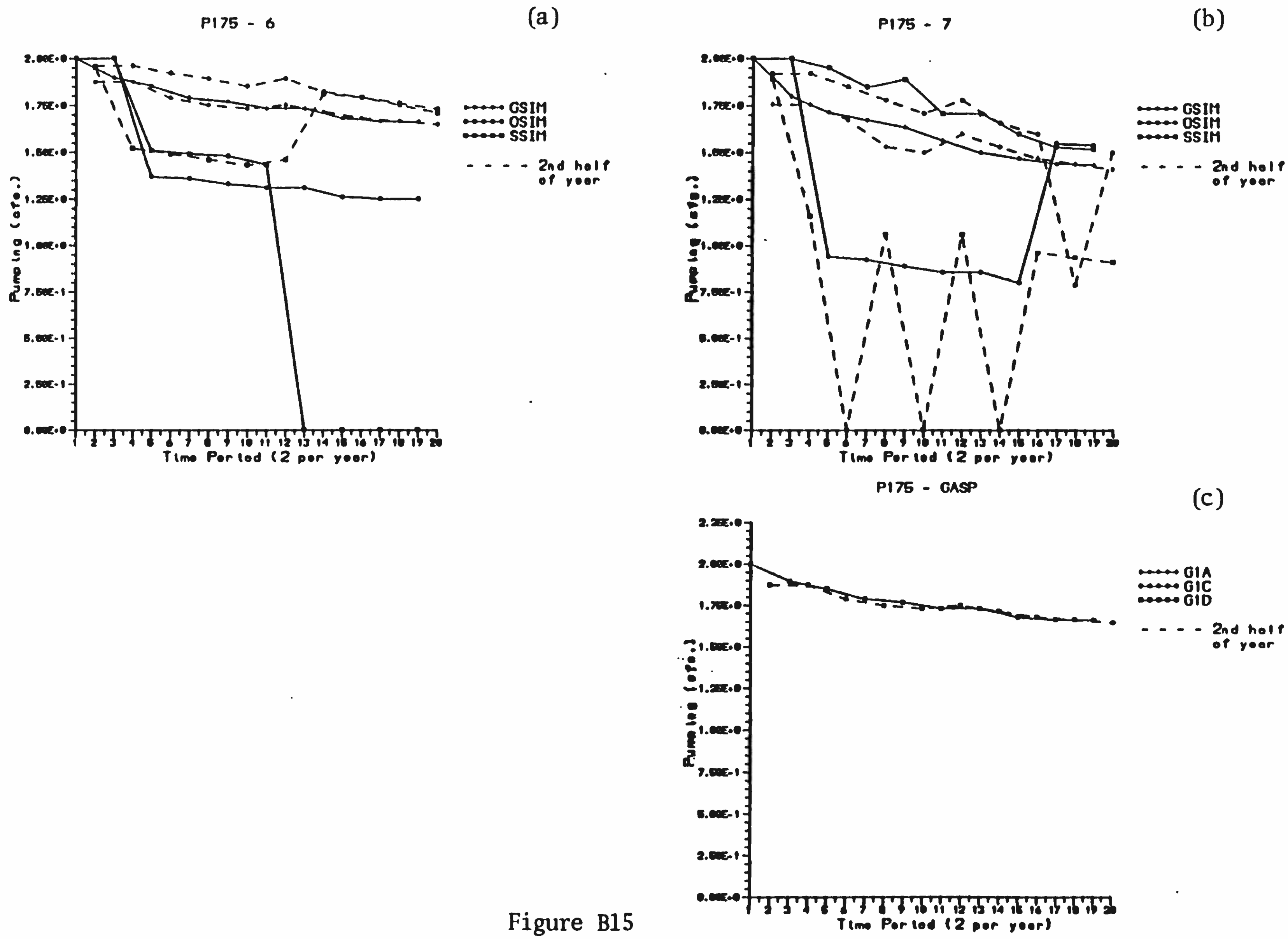
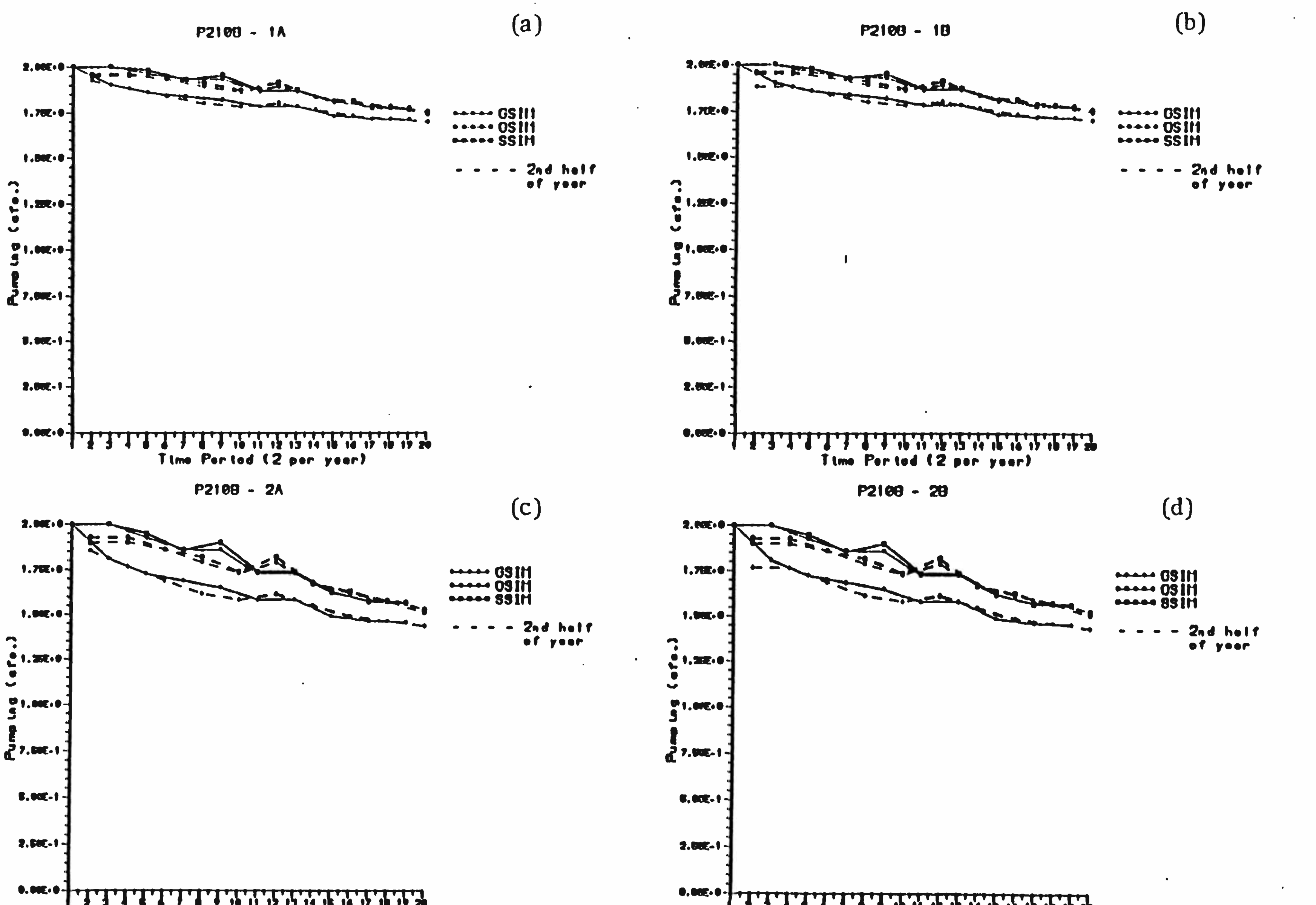
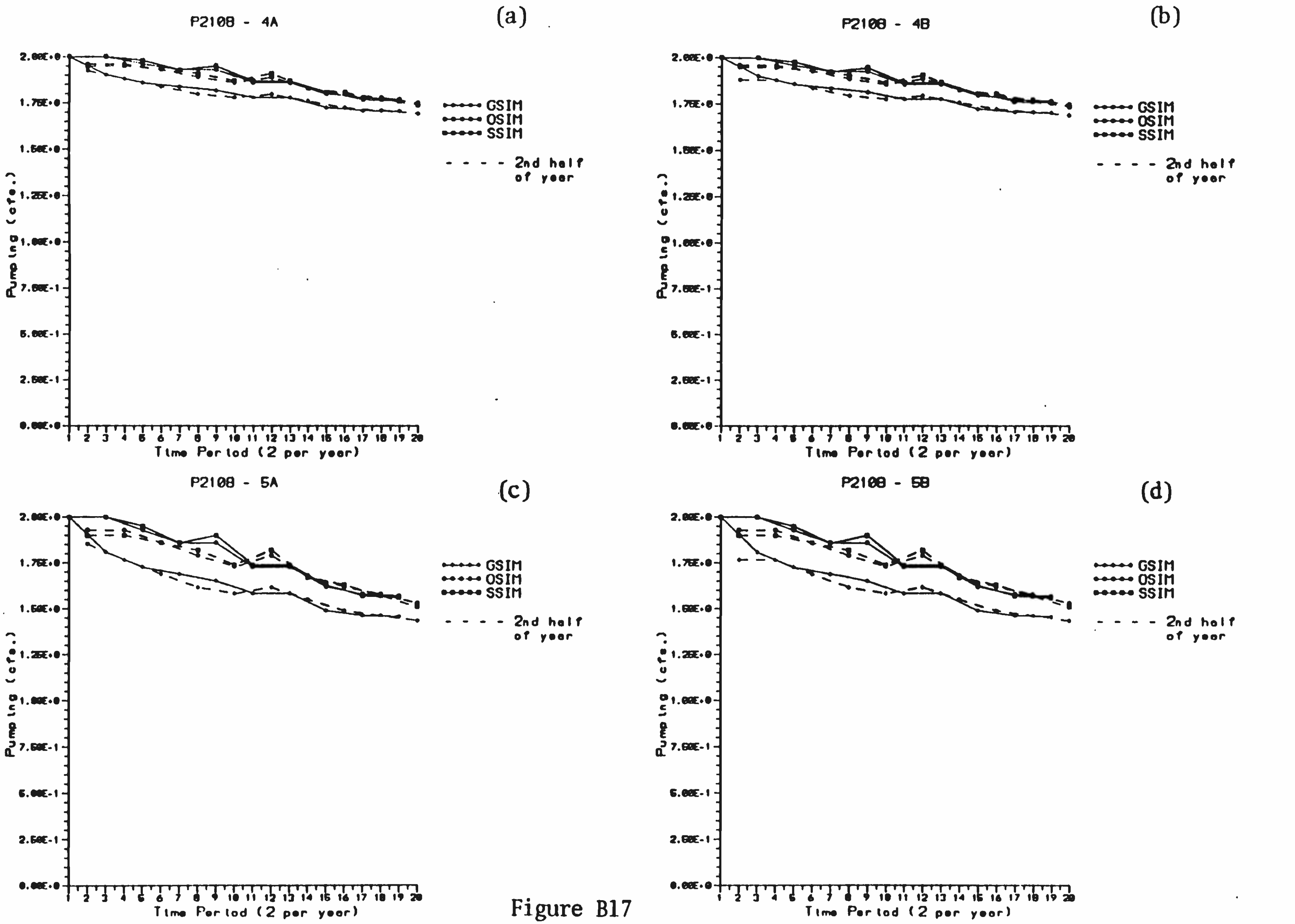

P175 - 6
(a)
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)
P175 - 7
(b)
GSIM
OSIM
SSIM
2nd half of year
Pumping (cfs.)
Time Period (2 per year)
P175 - GASP
(c)
G1A
G1C
G1D
2nd half of year
Pumping (cfs.)
Time Period (2 per year)

Figure B15



P2100 - 1A
(a)
P2100 - 1B
(b)
P2100 - 2A
(c)
P2100 - 2B
(d)
GSIM
OSIM
SSIM
2nd half of year
Pumping (afe.)
Time Period (2 per year)

Figure B16



P2108 - 4A
(a)
P2108 - 4B
(b)
P2108 - 5A
(c)
P2108 - 5B
(d)
Pumping (cfs.)
Time Period (2 per year)
2.00E+0
1.75E+0
1.50E+0
1.25E+0
1.00E+0
7.50E-1
5.00E-1
2.50E-1
0.00E+0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
GSIM
OSIM
SSIM
2nd half of year

Figure B17

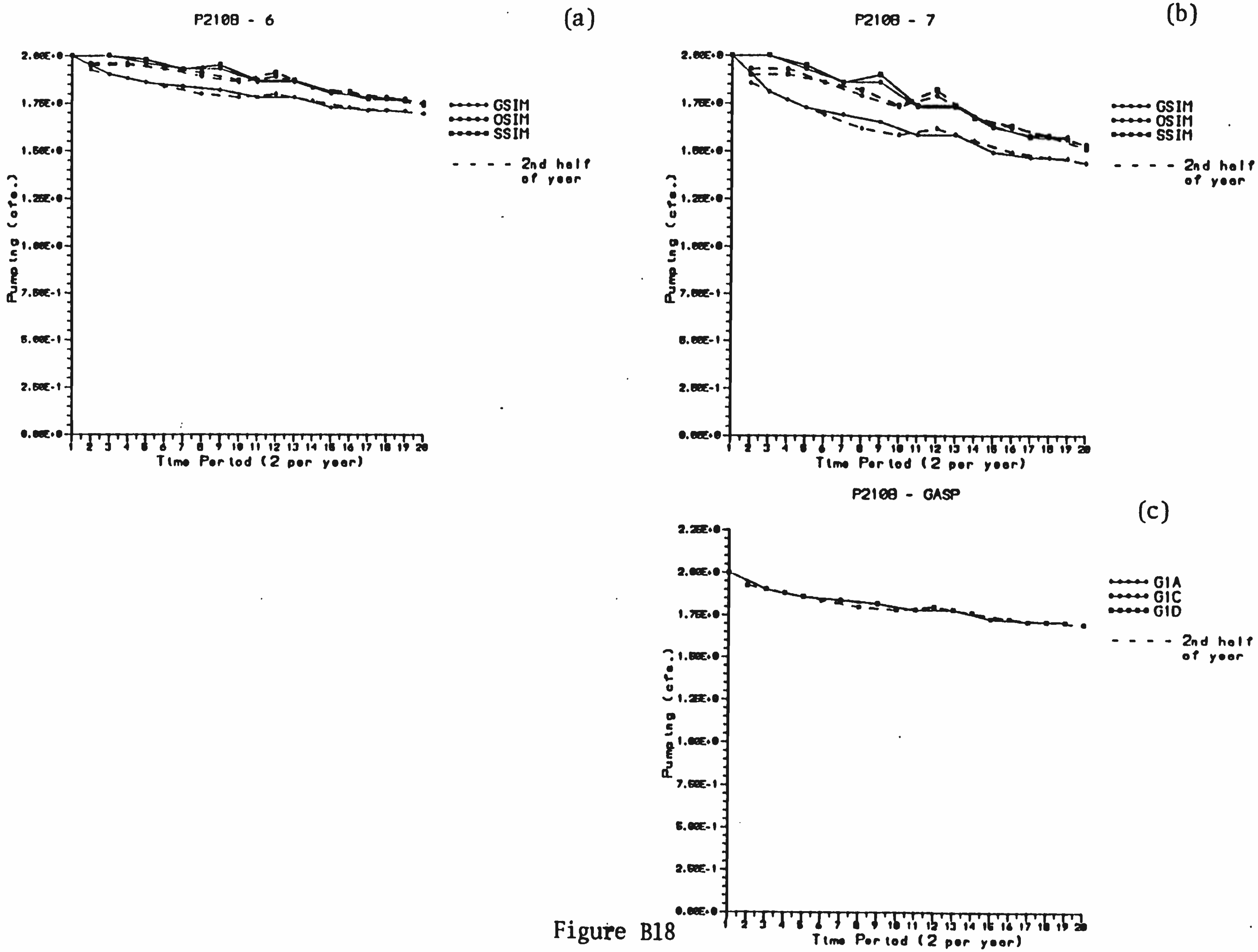

P210B - 6
(a)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year
P210B - 7
(b)
Pumping (cfs.)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year
P210B - GASP
(c)
Pumping (cfs.)
Time Period (2 per year)
G1A
G1C
G1D
2nd half of year

Figure B18

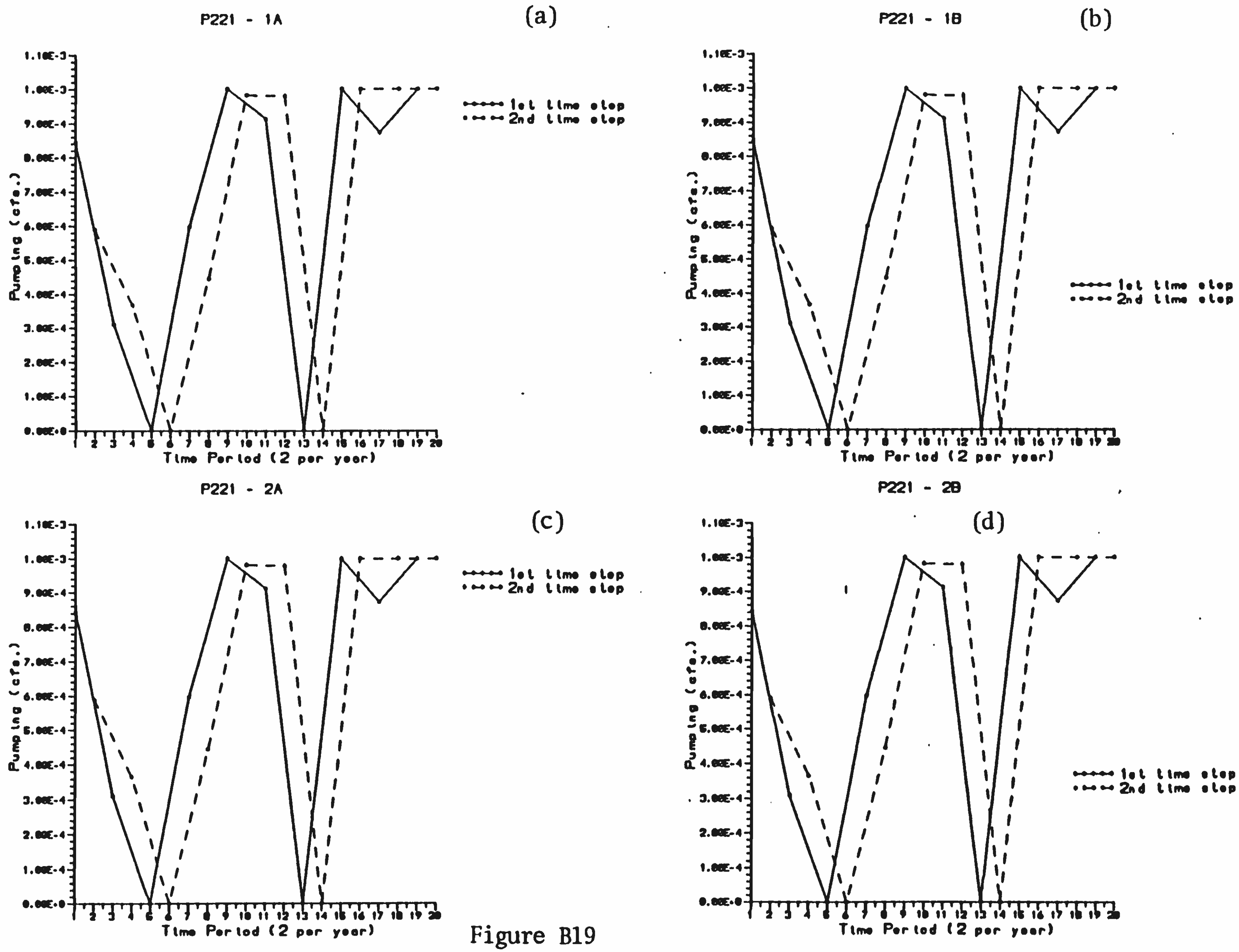
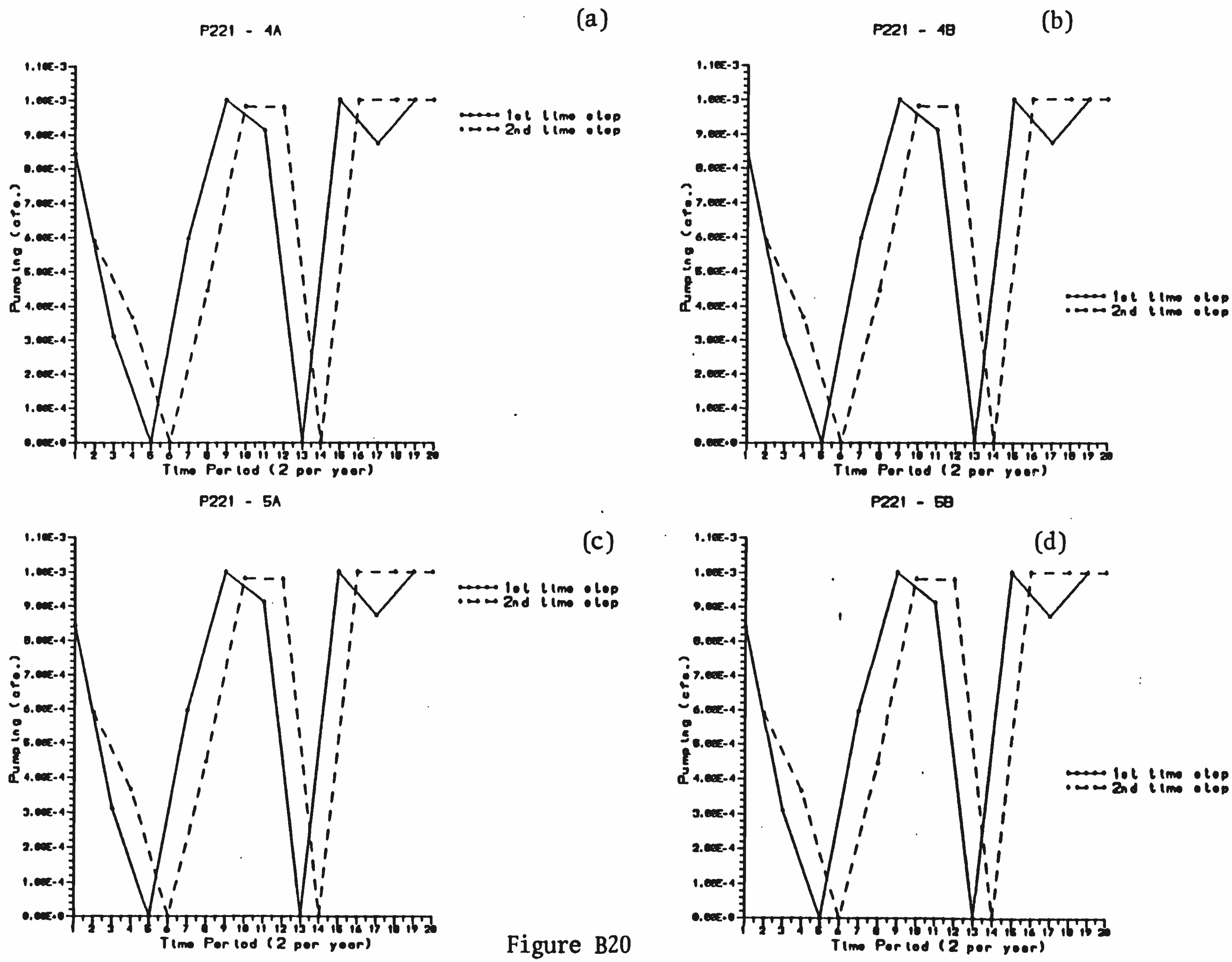
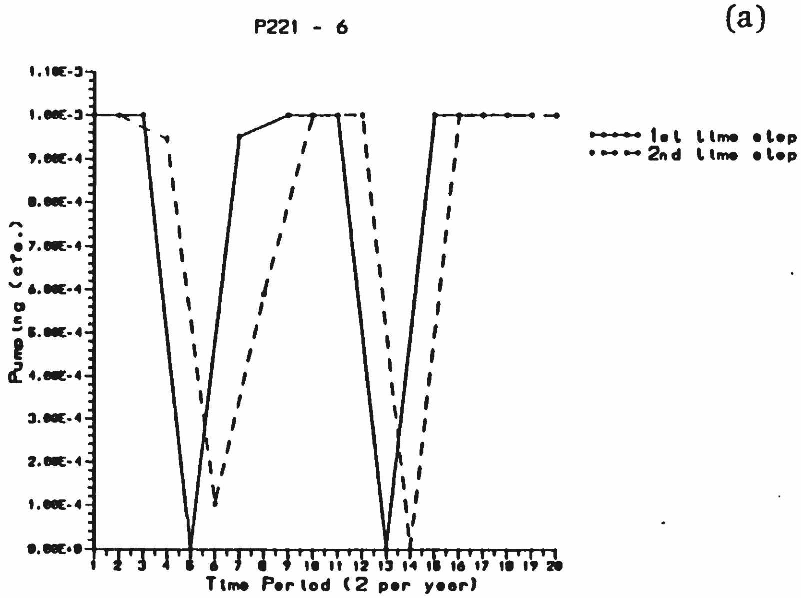

P221 - 1A
(a)
P221 - 1B
(b)
P221 - 2A
(c)
P221 - 2B
(d)
Pumping (cfs.)
Time Period (2 per year)
1st time step
2nd time step
1.10E-3
1.00E-3
9.00E-4
8.00E-4
7.00E-4
6.00E-4
5.00E-4
4.00E-4
3.00E-4
2.00E-4
1.00E-4
0.00E+0

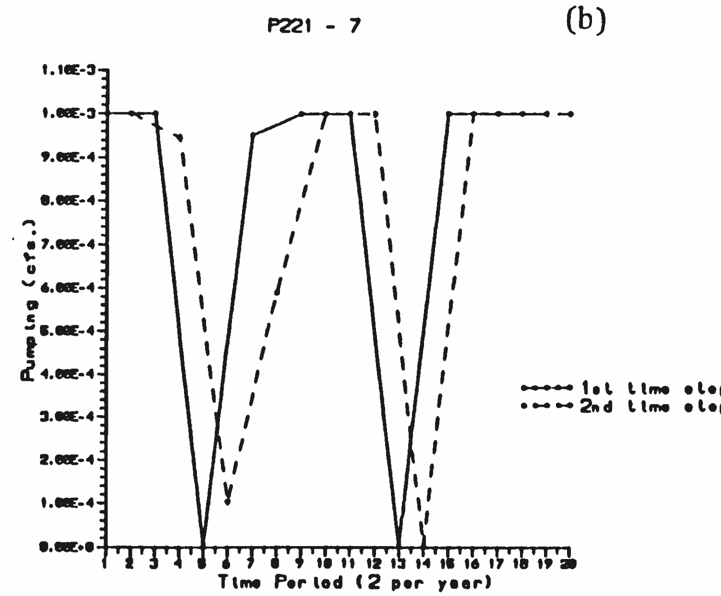
Figure B19



(a)
P221 - 4A
Pumping (cfs.)
Time Period (2 per year)
1st time step
2nd time step
(b)
P221 - 4B
Pumping (cfs.)
Time Period (2 per year)
1st time step
2nd time step
(c)
P221 - 5A
Pumping (cfs.)
Time Period (2 per year)
1st time step
2nd time step
(d)
P221 - 5B
Pumping (cfs.)
Time Period (2 per year)
1st time step
2nd time step

Figure B20


P221 - 6
(a)
Pumping (cfs.)
1.10E-3
1.00E-3
9.00E-4
8.00E-4
7.00E-4
6.00E-4
5.00E-4
4.00E-4
3.00E-4
2.00E-4
1.00E-4
0.00E+0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
1st time step
2nd time step


P221 - 7
(b)
Pumping (cfs.)
1.10E-3
1.00E-3
9.00E-4
8.00E-4
7.00E-4
6.00E-4
5.00E-4
4.00E-4
3.00E-4
2.00E-4
1.00E-4
0.00E+0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
1st time step
2nd time step

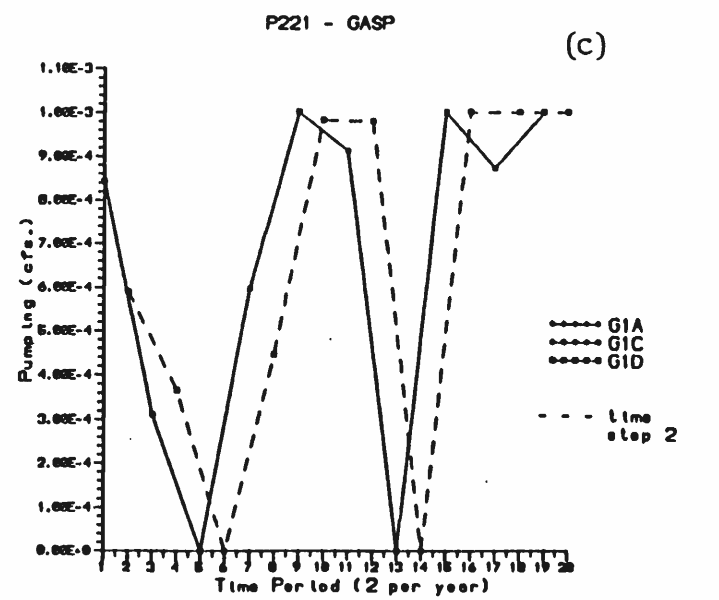

P221 - GASP
(c)
Pumping (cfs.)
1.10E-3
1.00E-3
9.00E-4
8.00E-4
7.00E-4
6.00E-4
5.00E-4
4.00E-4
3.00E-4
2.00E-4
1.00E-4
0.00E+0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
G1A
G1C
G1D
time step 2

Figure B21

APPENDIX C

Drawdown Plots

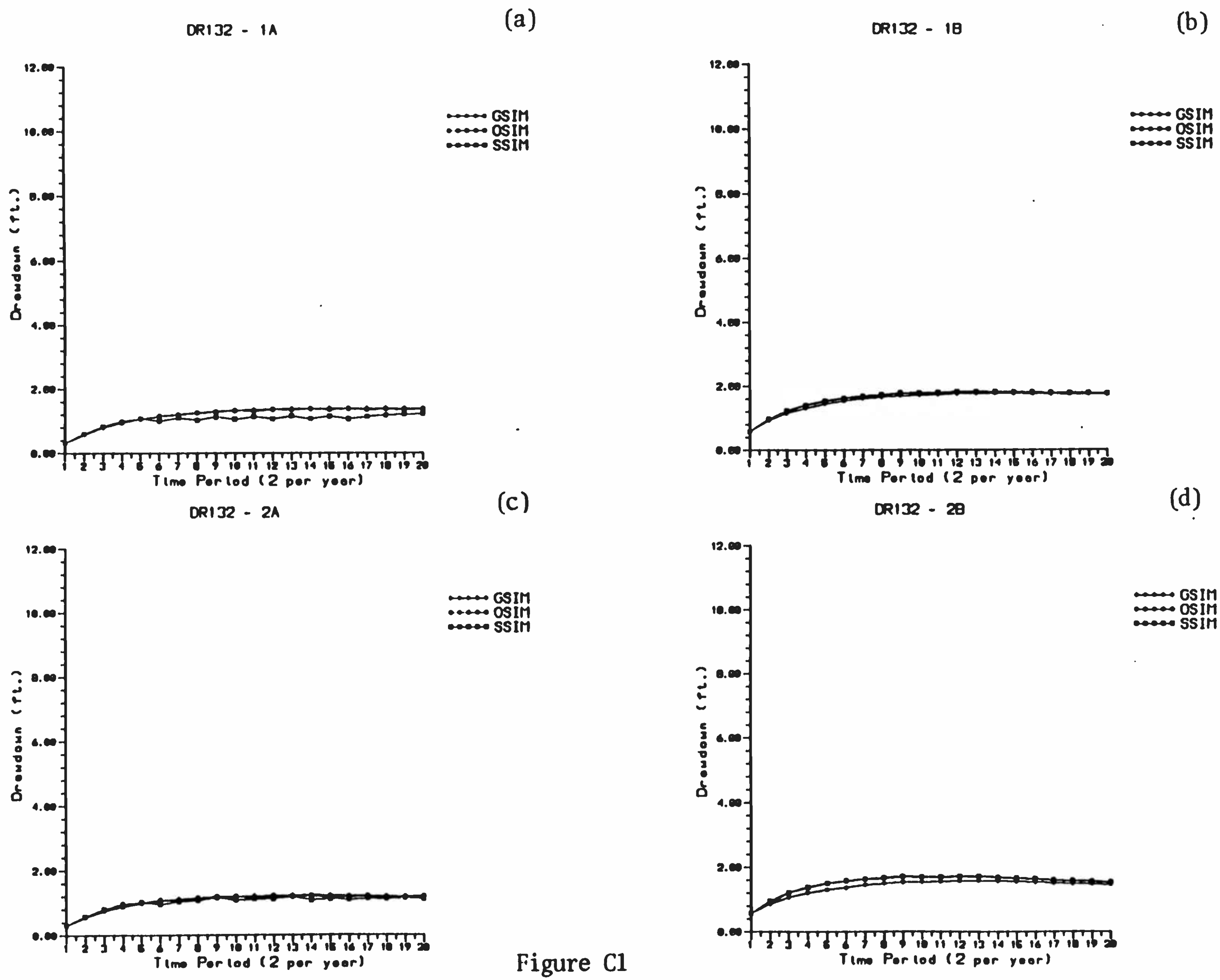

(a)
DR132 - 1A
(b)
DR132 - 1B
(c)
DR132 - 2A
(d)
DR132 - 2B
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C1

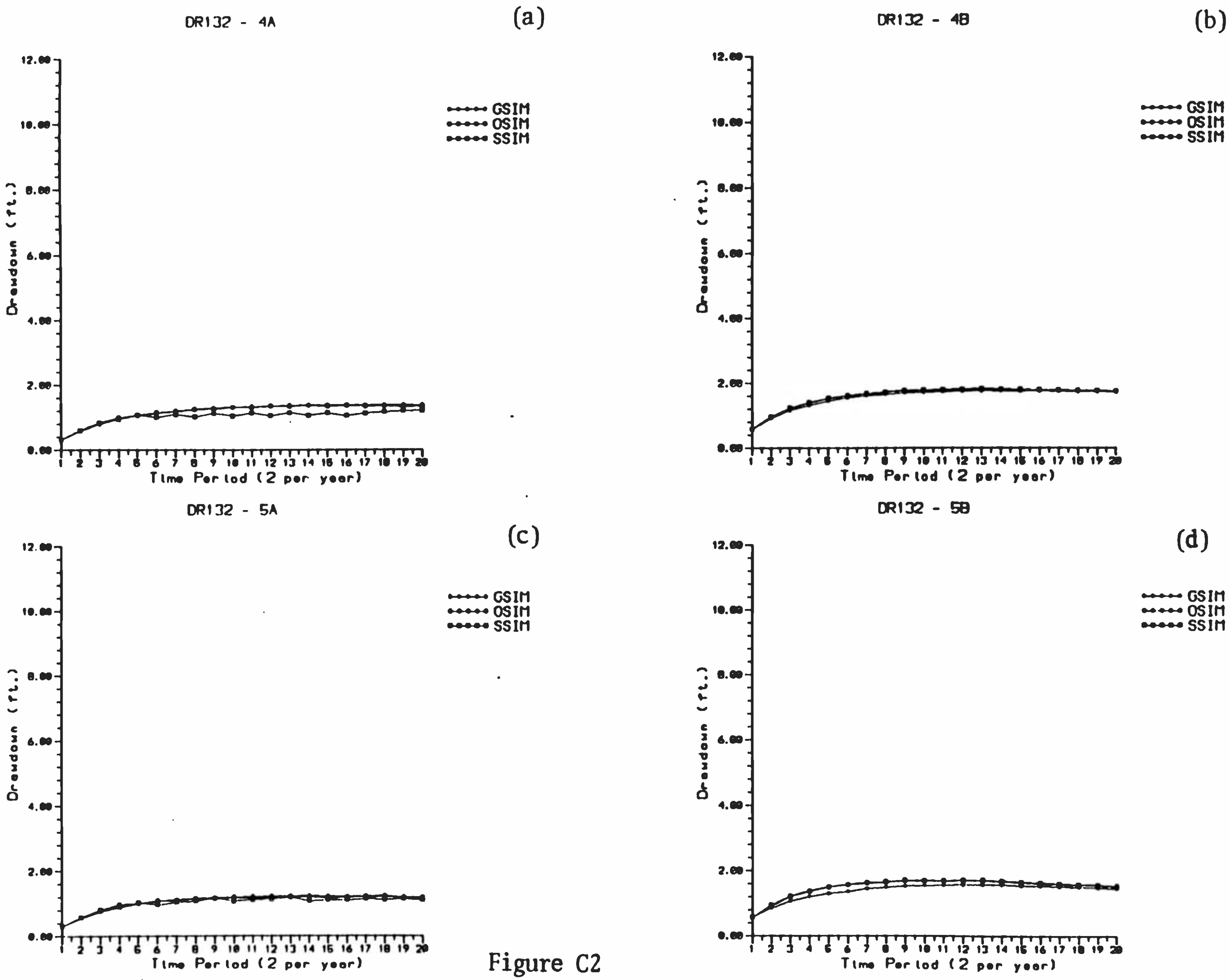
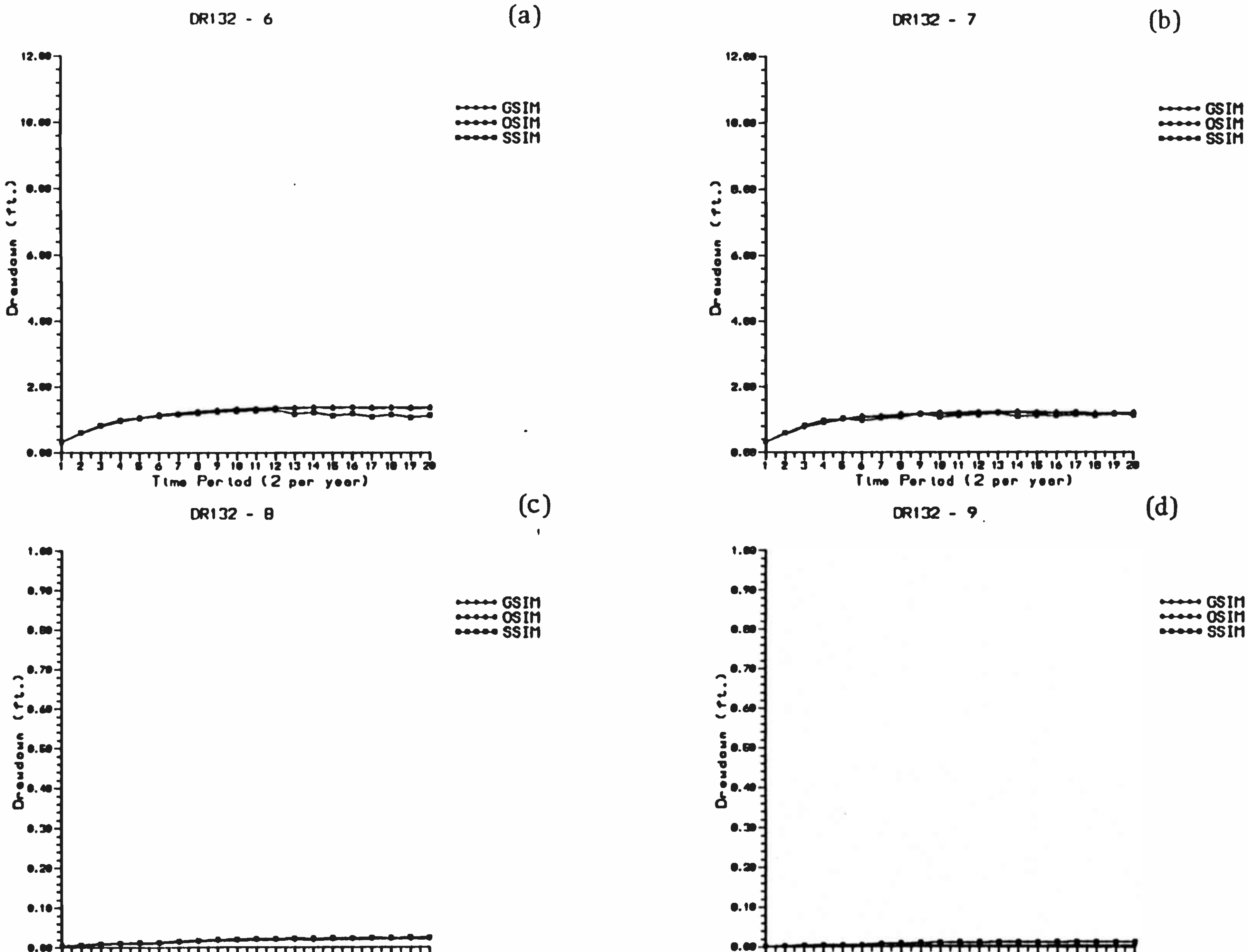

DR132 - 4A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR132 - 4B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR132 - 5A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR132 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C2



DR132 - 6
(a)
DR132 - 7
(b)
DR132 - 8
(c)
DR132 - 9
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C3

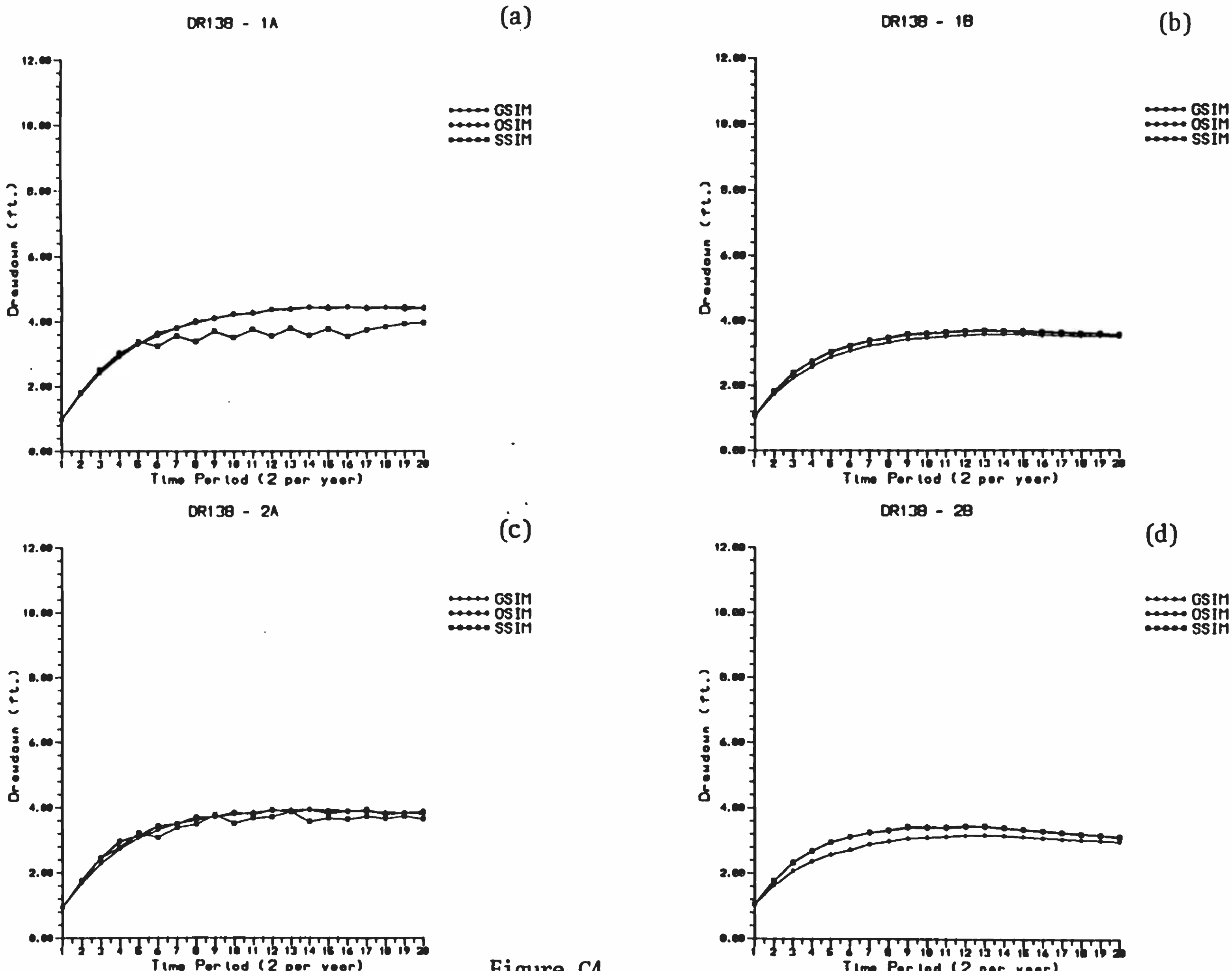

DR138 - 1A
(a)
DR138 - 1B
(b)
DR138 - 2A
(c)
DR138 - 2B
(d)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C4

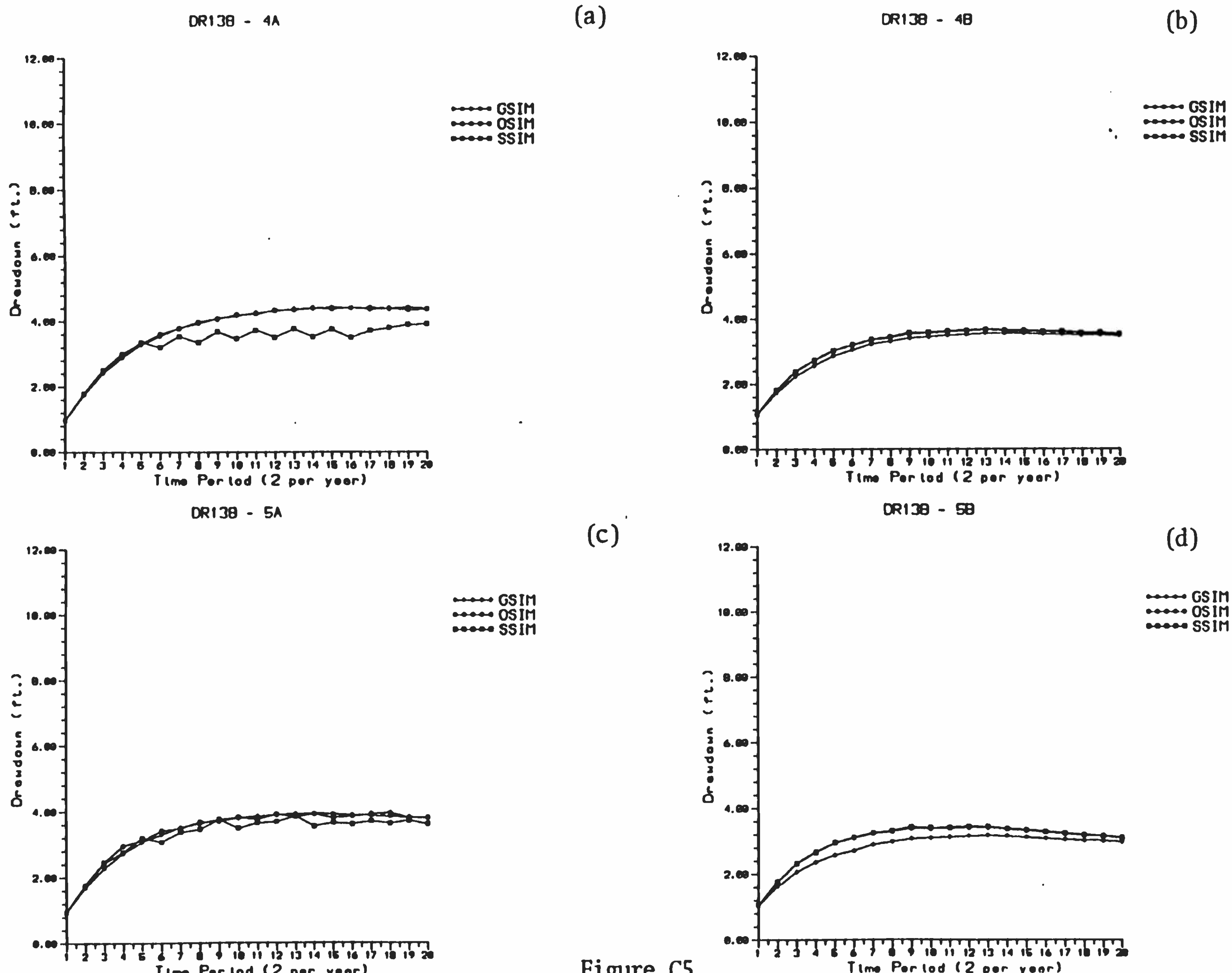

(a)
DR138 - 4A
(b)
DR138 - 4B
(c)
DR138 - 5A
(d)
DR138 - 5B
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
0.00
2.00
4.00
6.00
8.00
10.00
12.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure C5

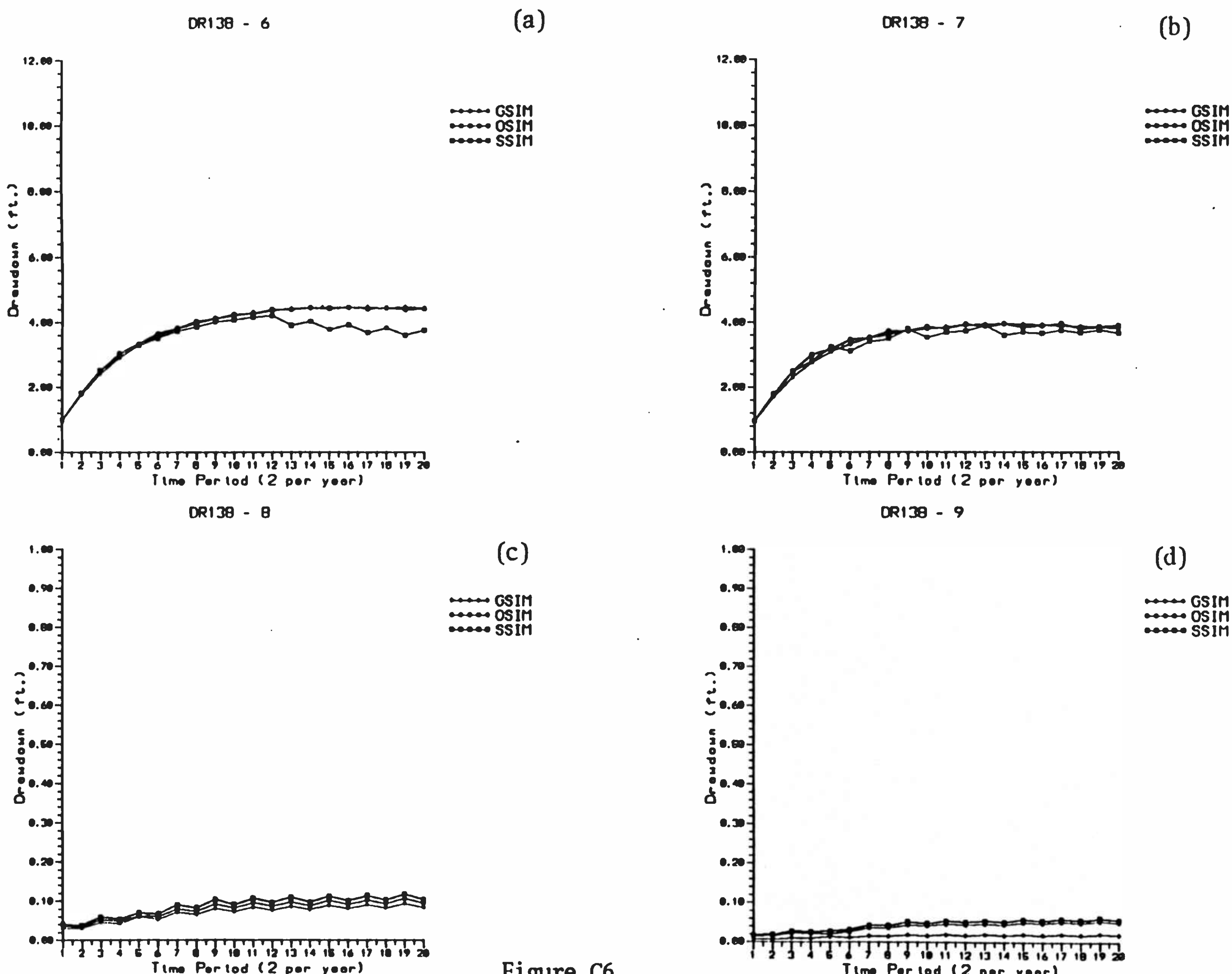
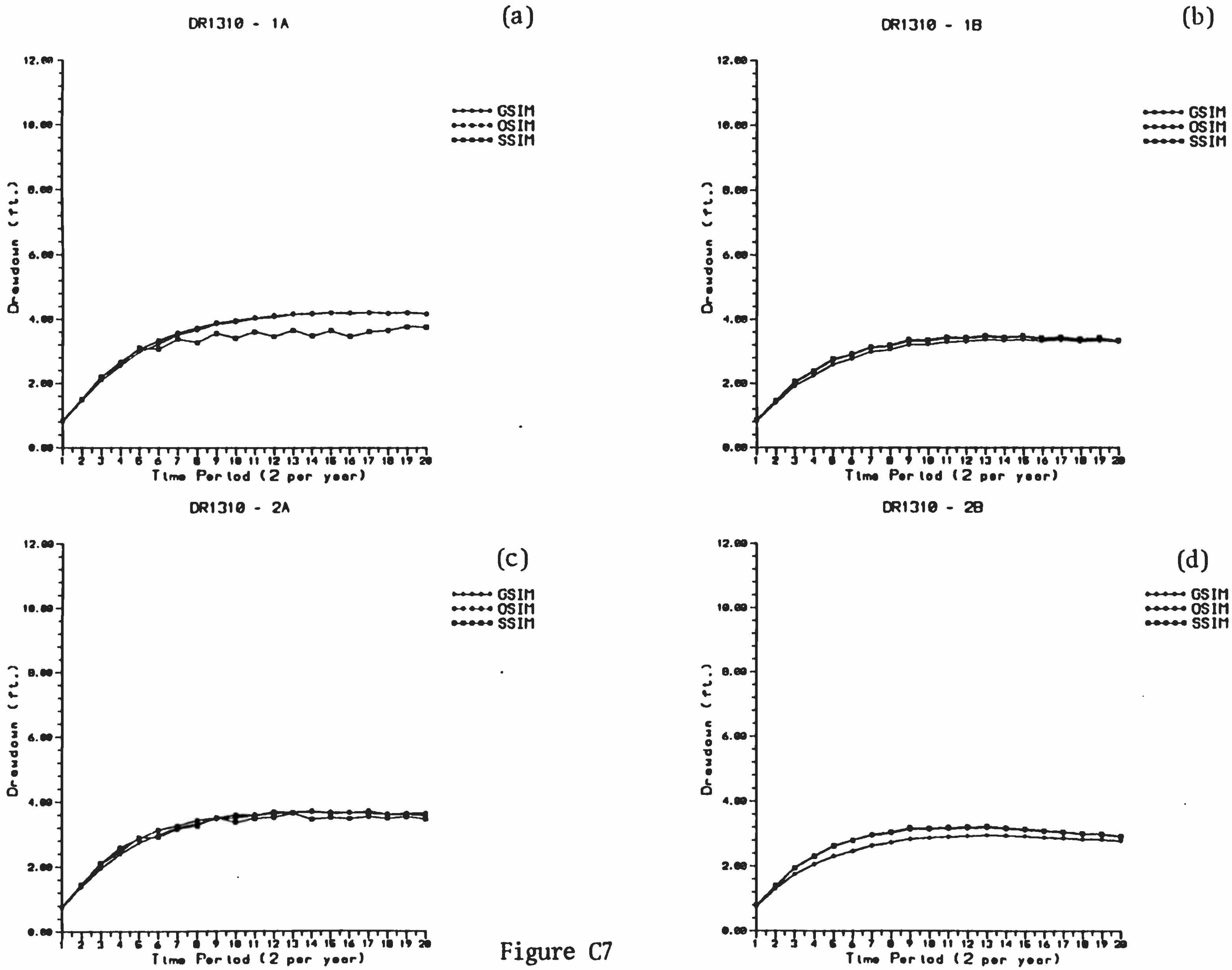

DR138 - 6
(a)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR138 - 7
(b)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR138 - 8
(c)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR138 - 9
(d)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C6



DR1310 - 1A
(a)
DR1310 - 1B
(b)
DR1310 - 2A
(c)
DR1310 - 2B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
0.00
2.00
4.00
6.00
8.00
10.00
12.00

Figure C7

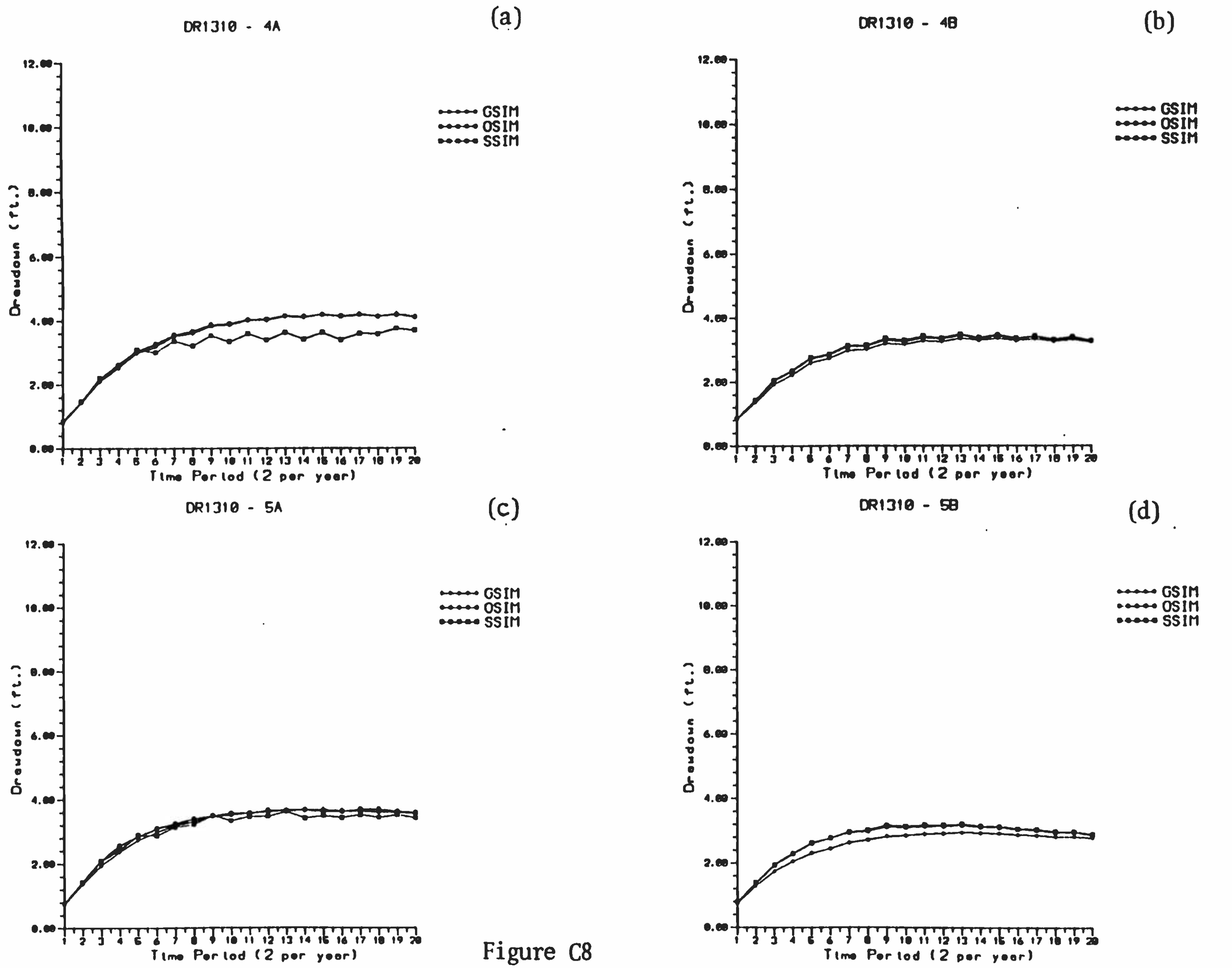

DR1310 - 4A
(a)
DR1310 - 4B
(b)
DR1310 - 5A
(c)
DR1310 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure C8

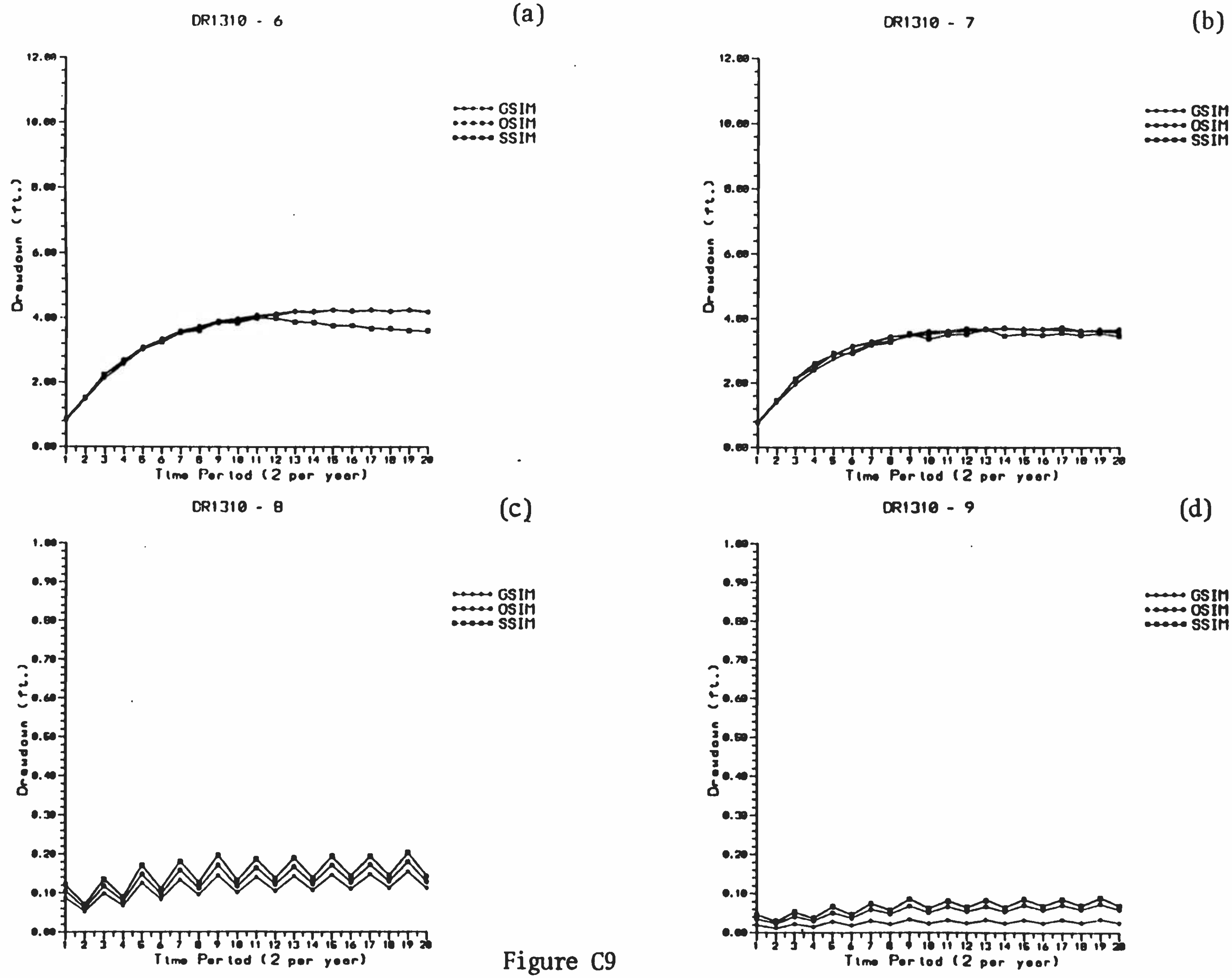

DR1310 - 6
(a)
DR1310 - 7
(b)
DR1310 - 8
(c)
DR1310 - 9
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C9

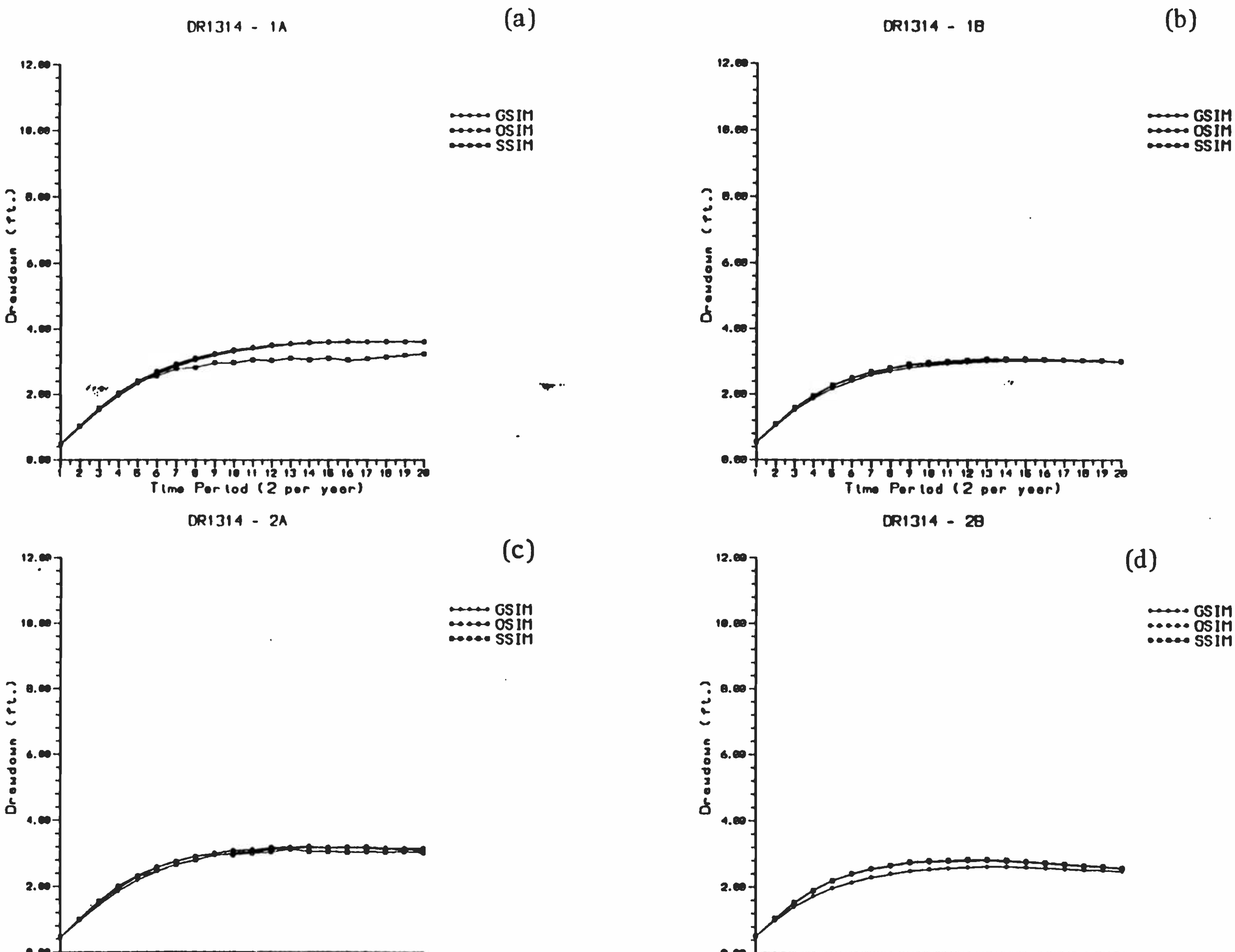

DR1314 - 1A
(a)
DR1314 - 1B
(b)
DR1314 - 2A
(c)
DR1314 - 2B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
12.00
10.00
8.00
6.00
4.00
2.00
0.00

Figure C 10

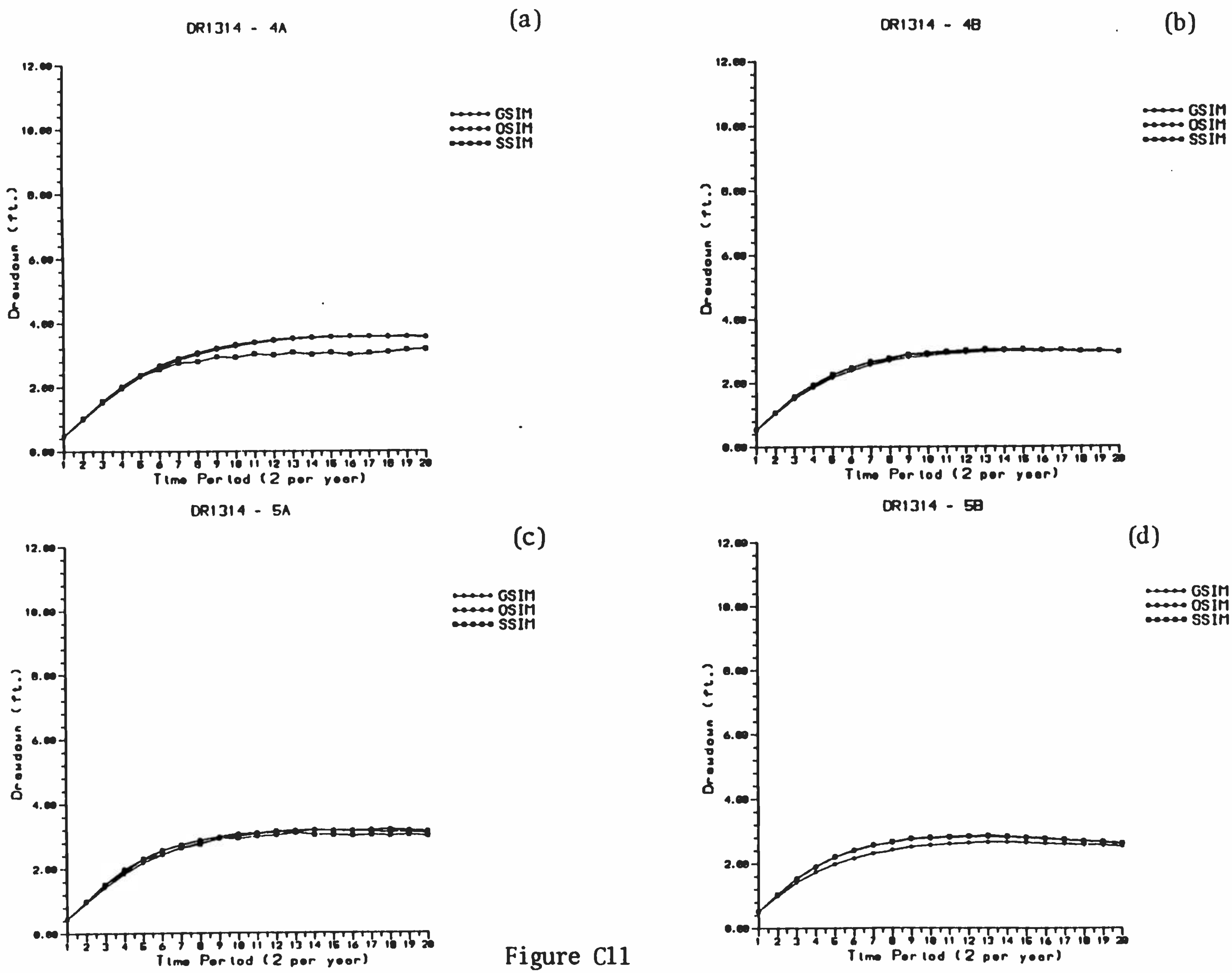

(a)
DR1314 - 4A
(b)
DR1314 - 4B
(c)
DR1314 - 5A
(d)
DR1314 - 5B
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure C11

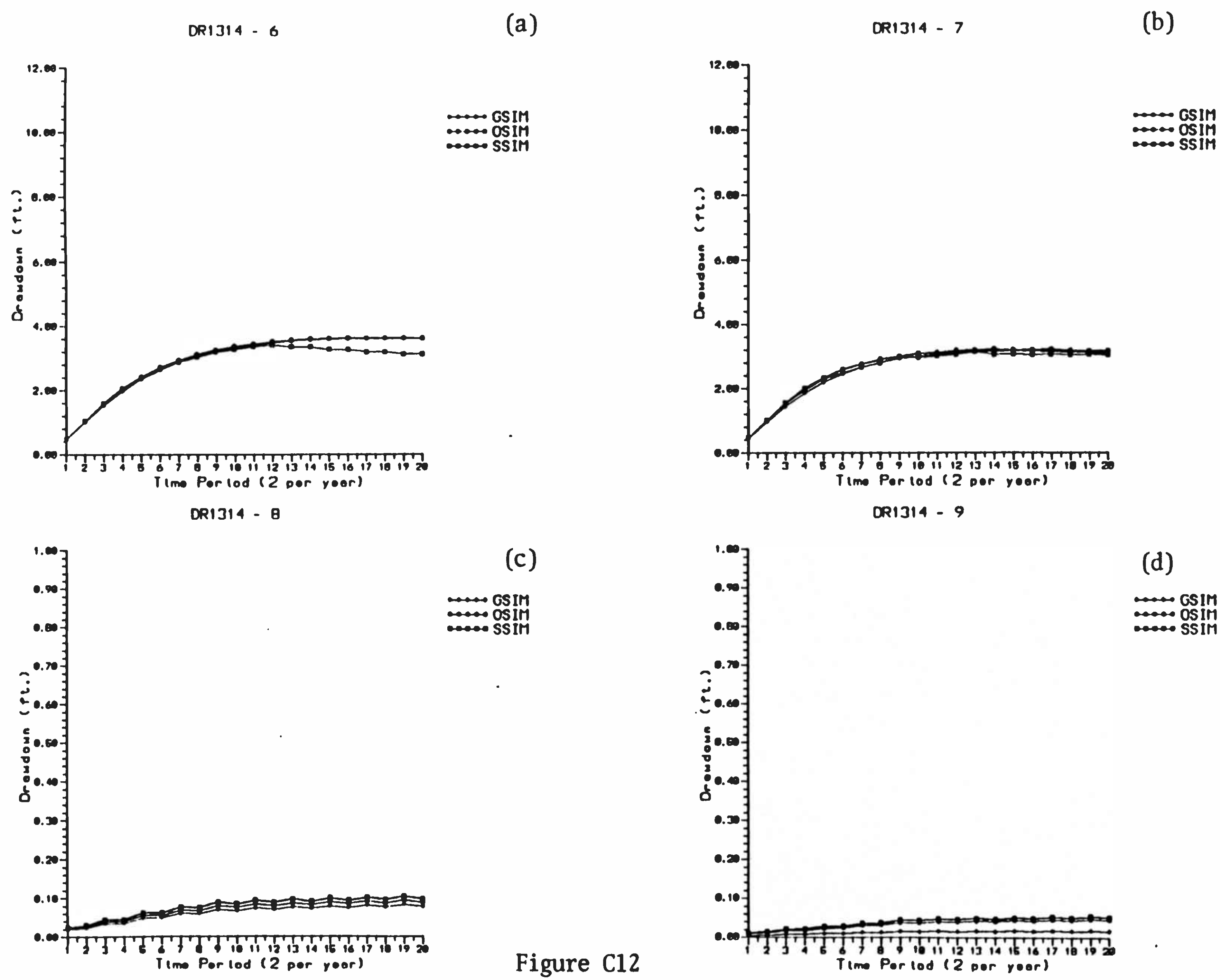

DR1314 - 6
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1314 - 7
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1314 - 8
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1314 - 9
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C12

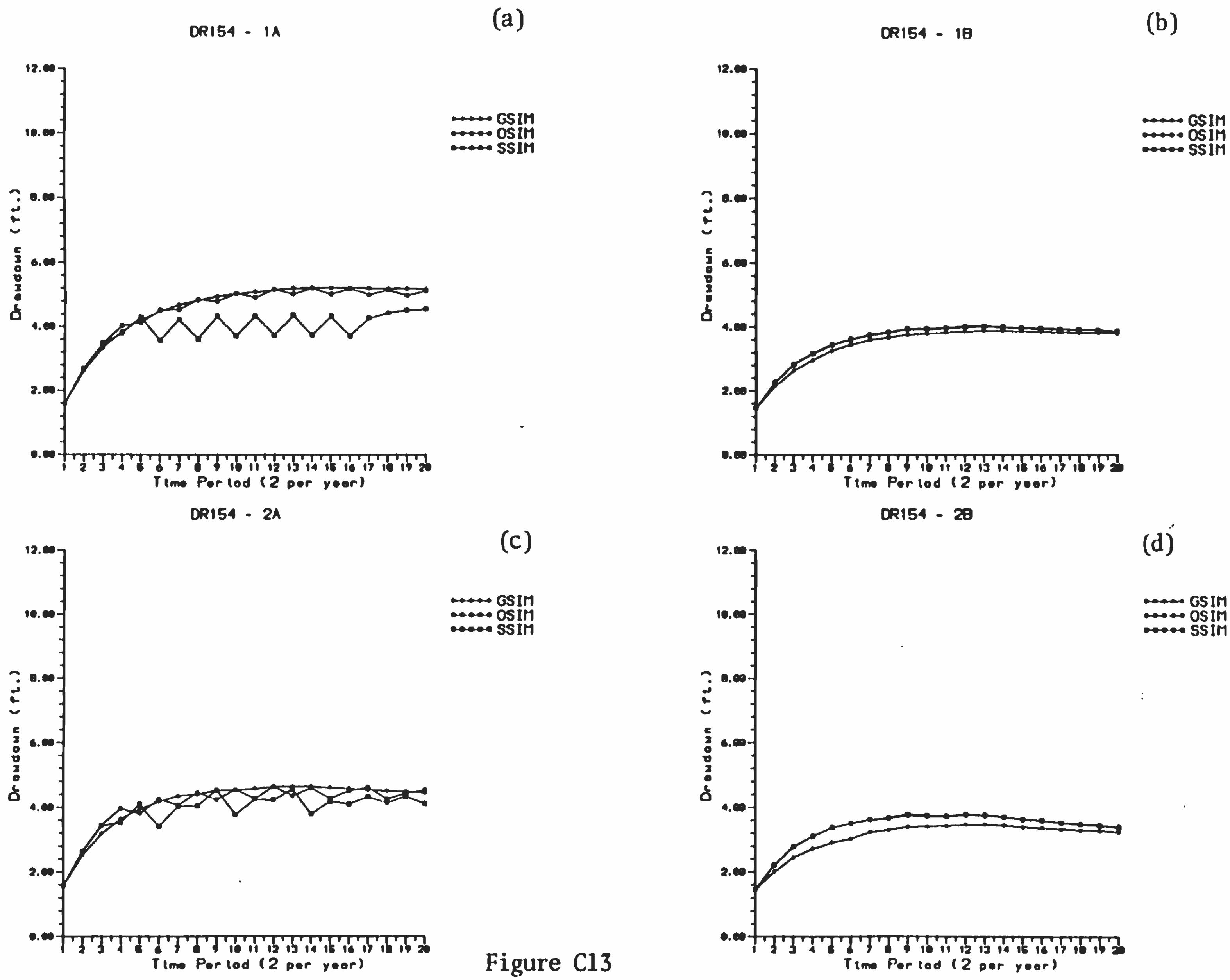

(a)
DR154 - 1A
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Drawdown (ft.)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
(b)
DR154 - 1B
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Drawdown (ft.)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
(c)
DR154 - 2A
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Drawdown (ft.)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
(d)
DR154 - 2B
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Drawdown (ft.)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C13

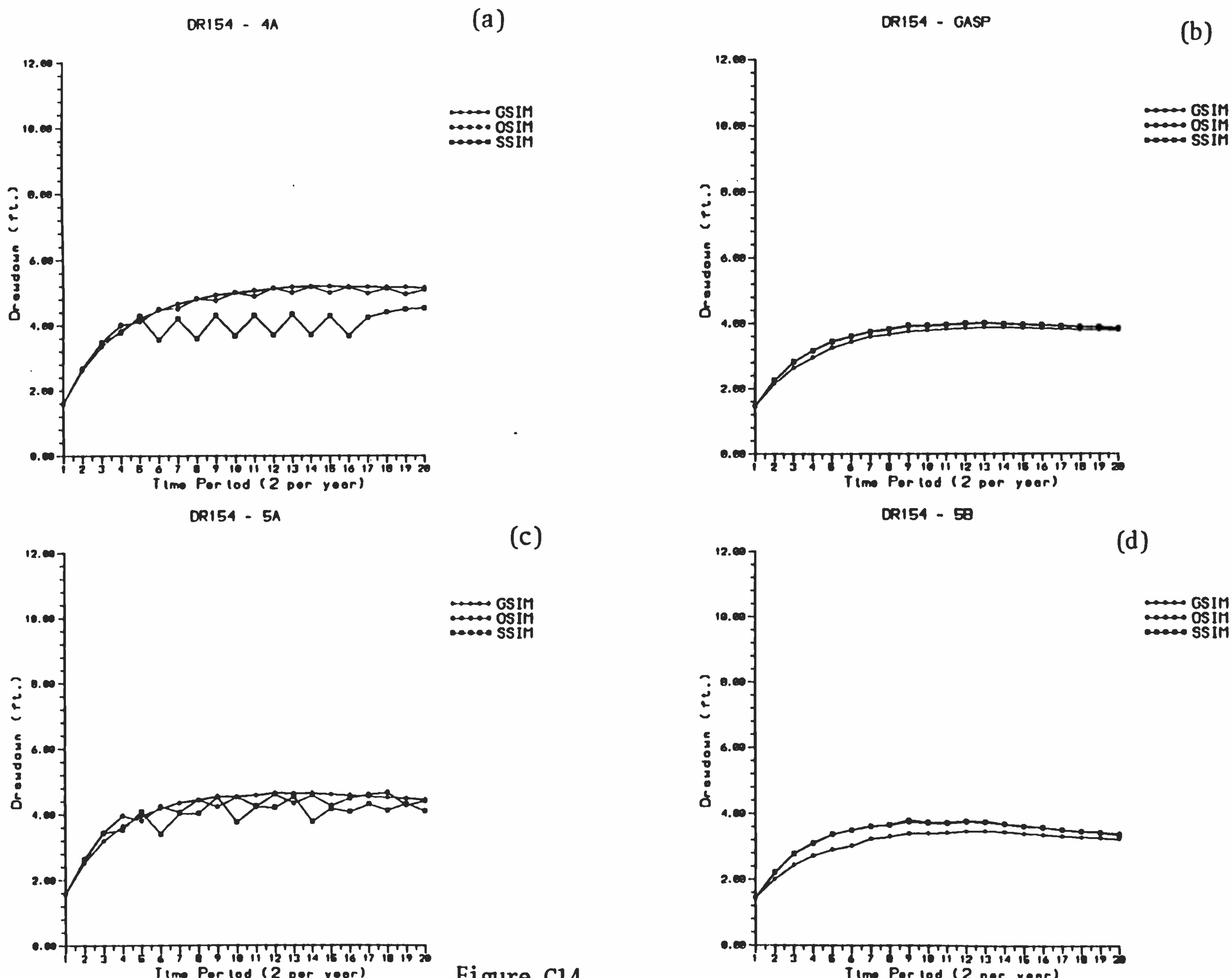

DR154 - 4A
(a)
DR154 - GASP
(b)
DR154 - 5A
(c)
DR154 - 5B
(d)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
12.00
10.00
8.00
6.00
4.00
2.00
0.00

Figure C14

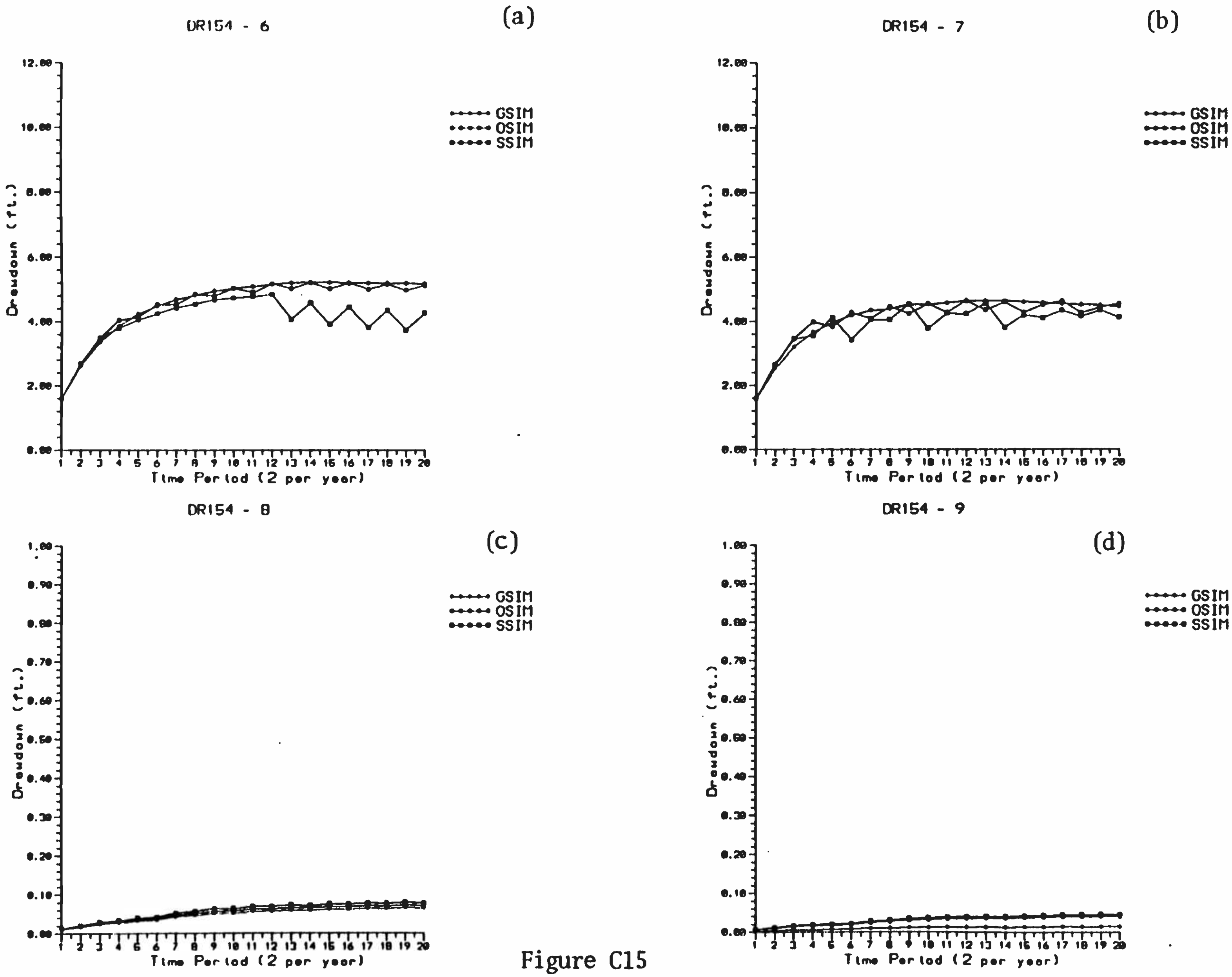
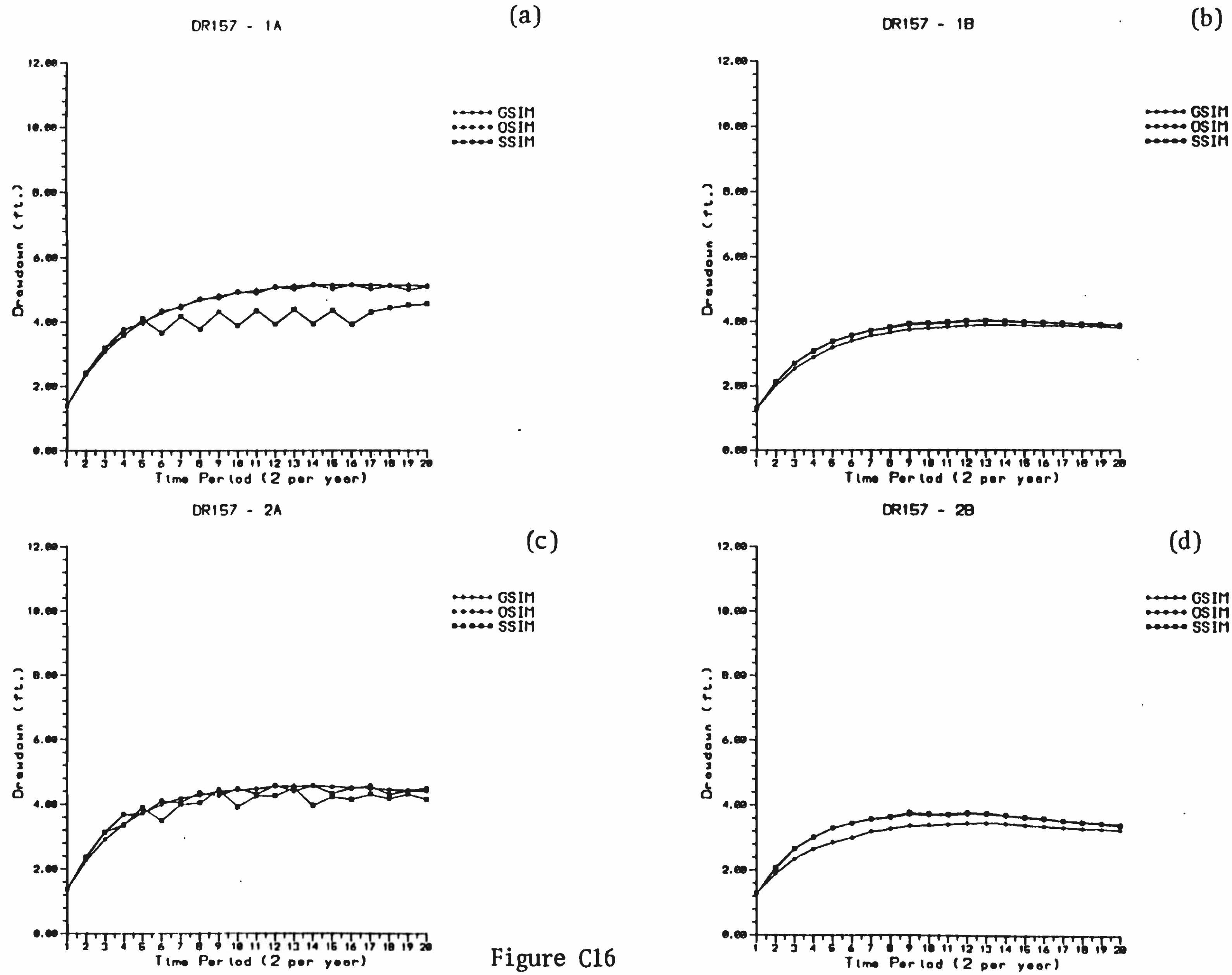

DR154 - 6
(a)
DR154 - 7
(b)
DR154 - 8
(c)
DR154 - 9
(d)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C15



(a)
DR157 - 1A
(b)
DR157 - 1B
(c)
DR157 - 2A
(d)
DR157 - 2B
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C16

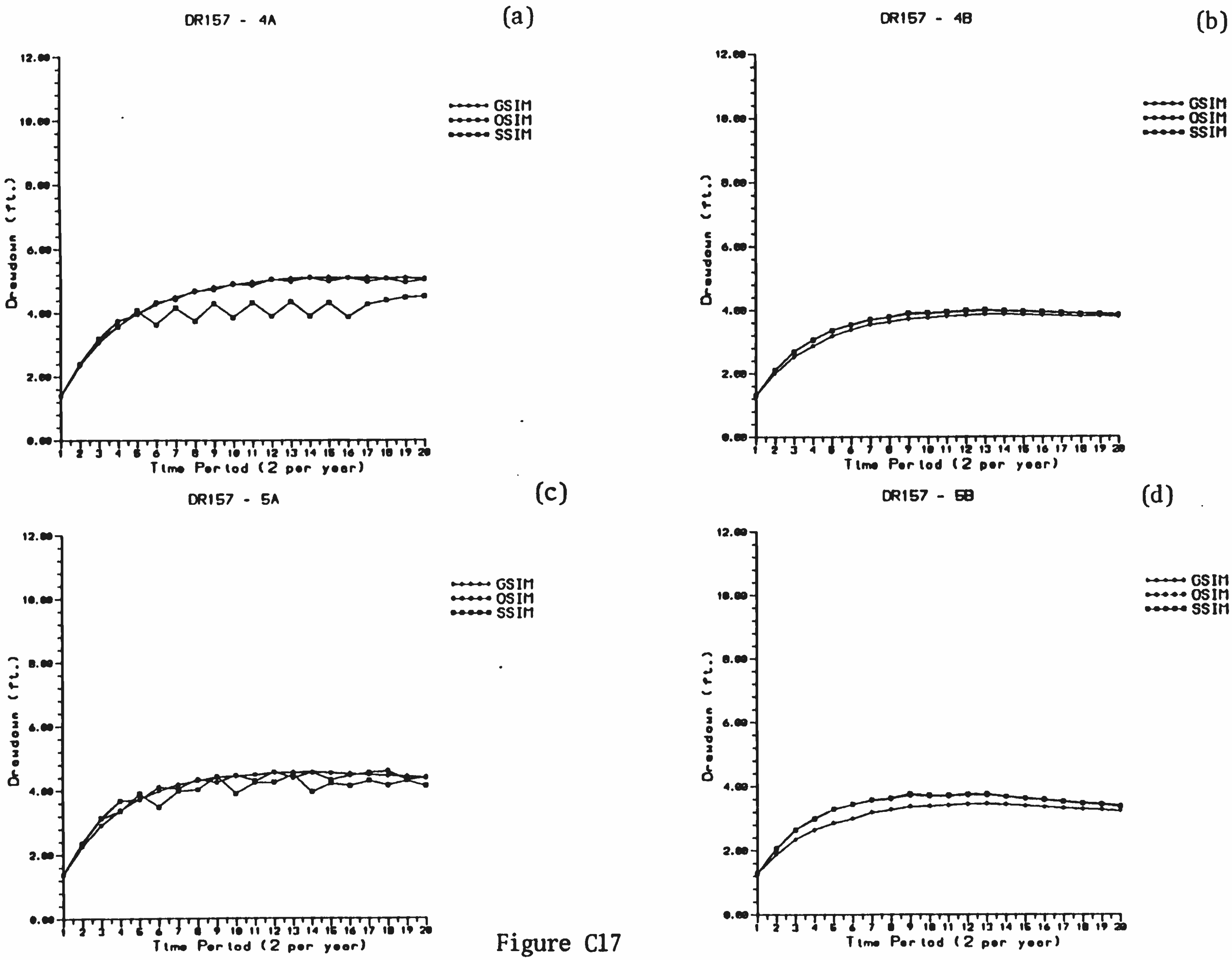
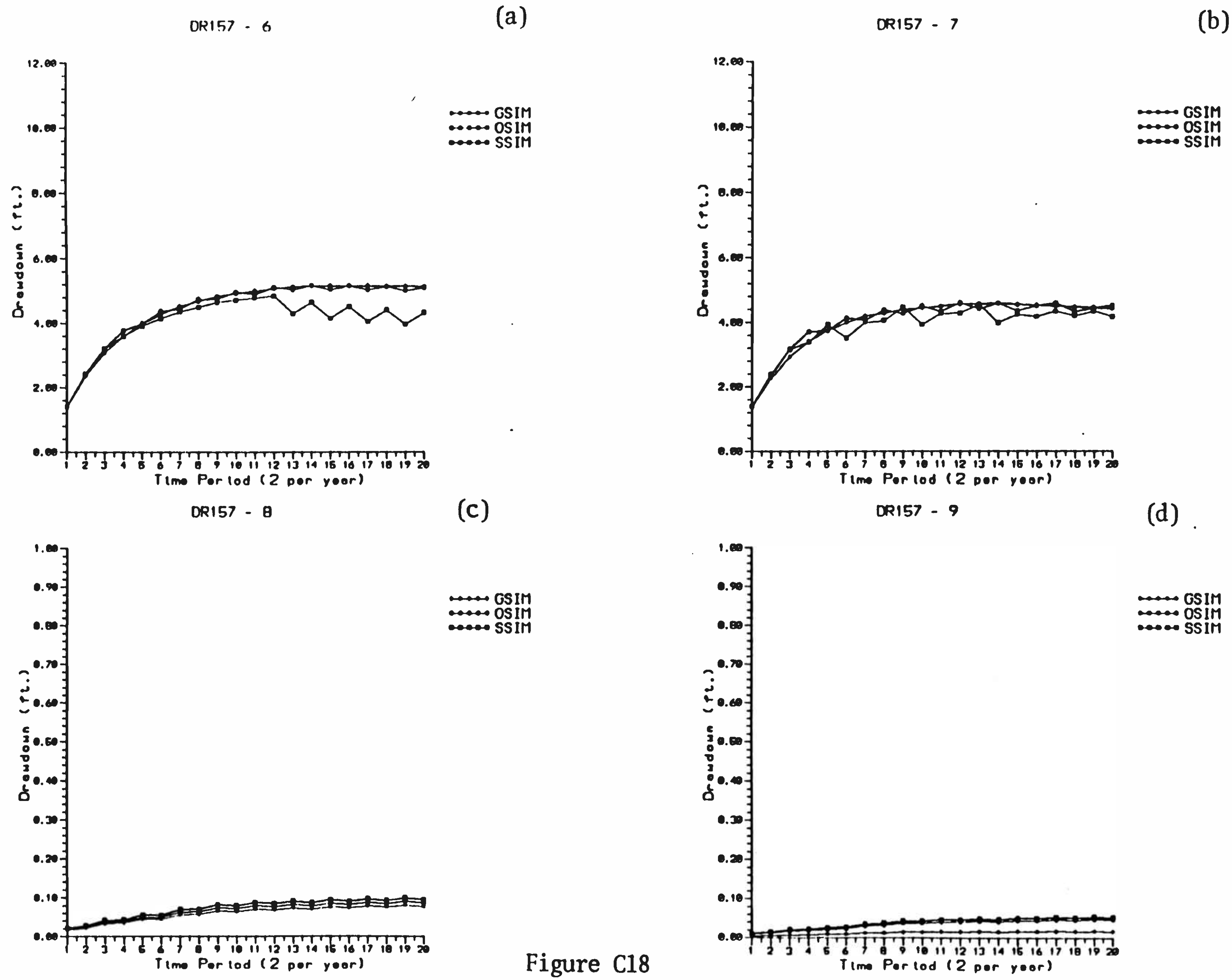

DR157 - 4A
(a)
DR157 - 4B
(b)
DR157 - 5A
(c)
DR157 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C17



DR157 - 6
(a)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR157 - 7
(b)
DR157 - 8
(c)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
DR157 - 9
(d)

Figure C18

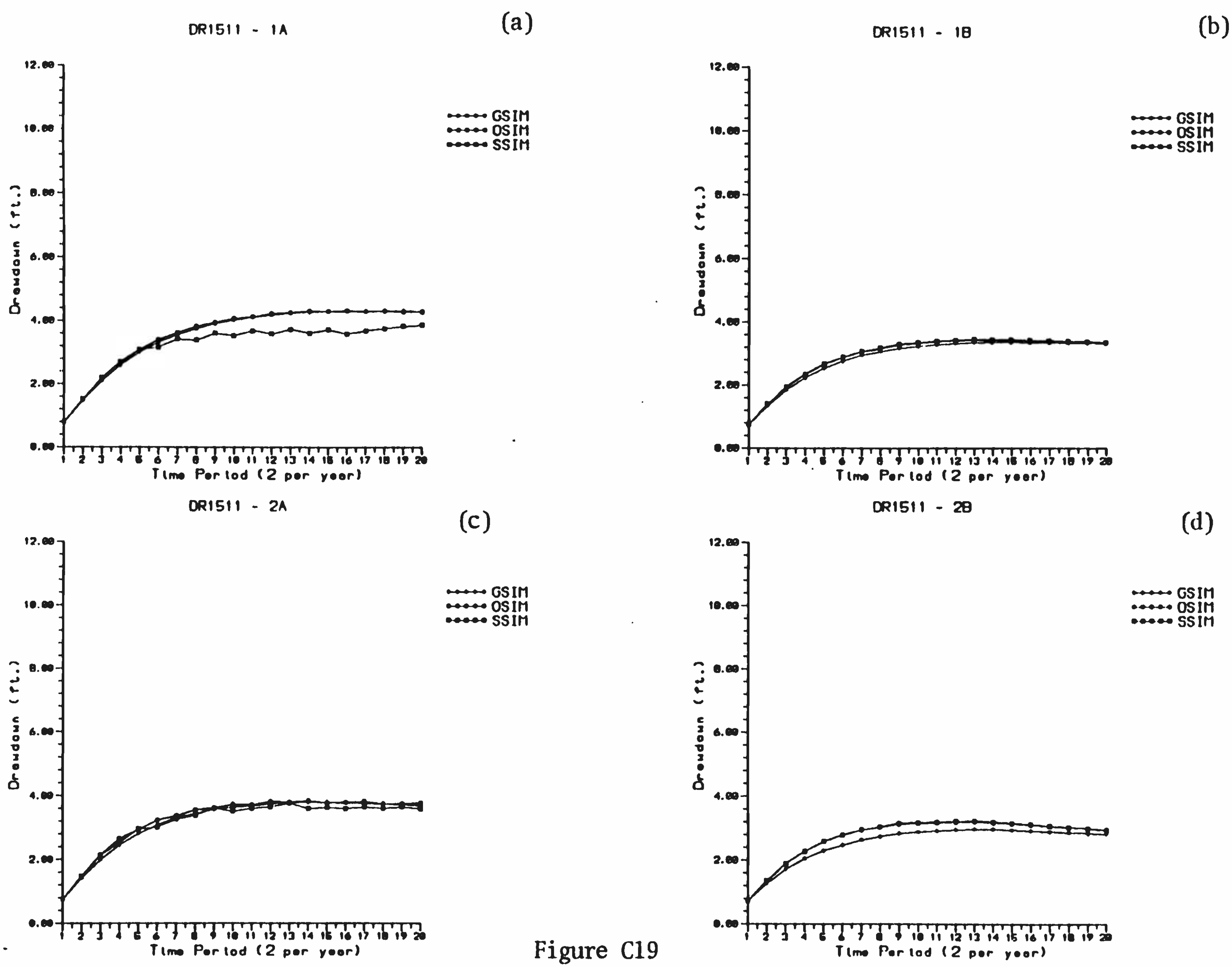

(a)
DR1511 - 1A
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
(b)
DR1511 - 1B
(c)
DR1511 - 2A
(d)
DR1511 - 2B

Figure C19

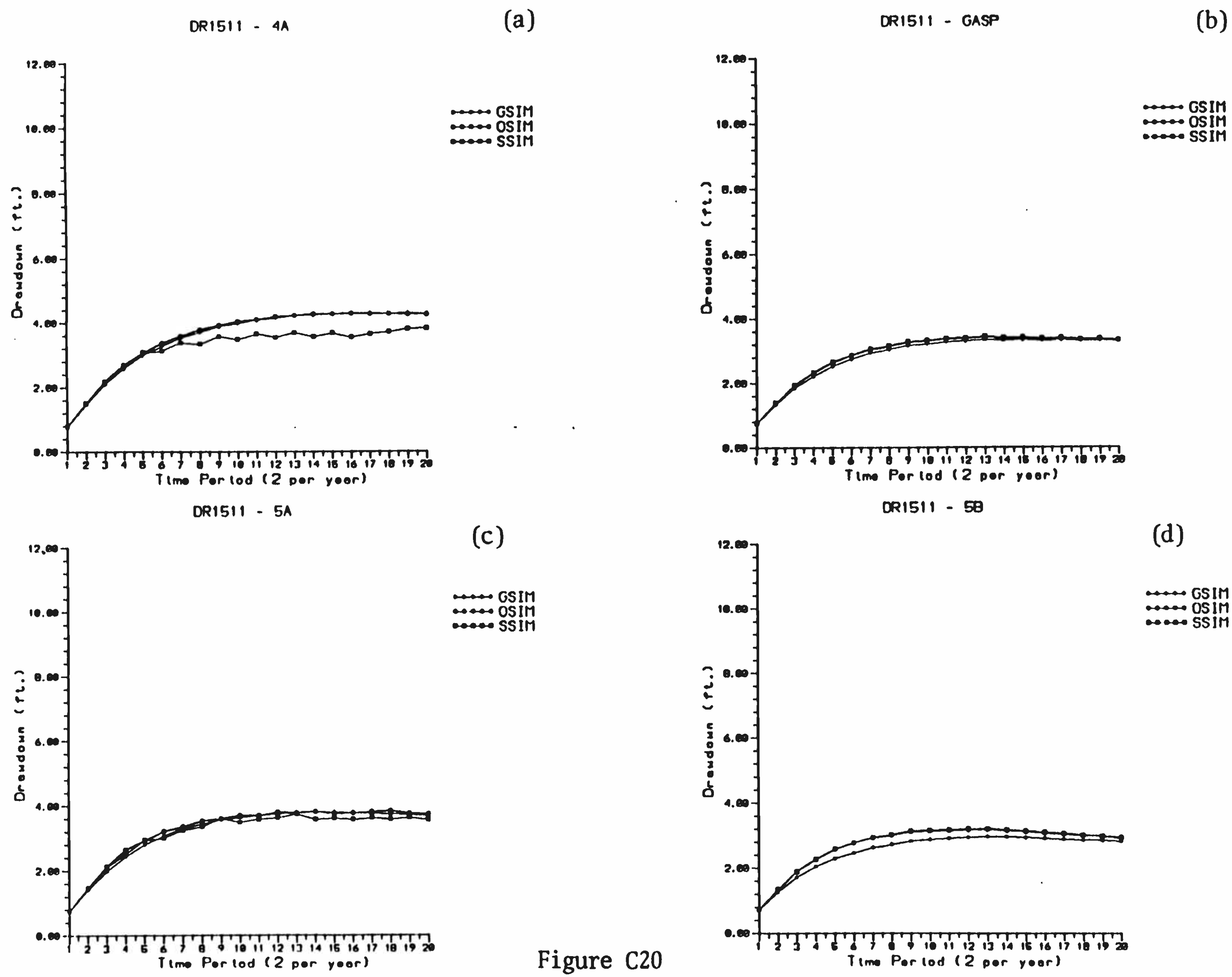
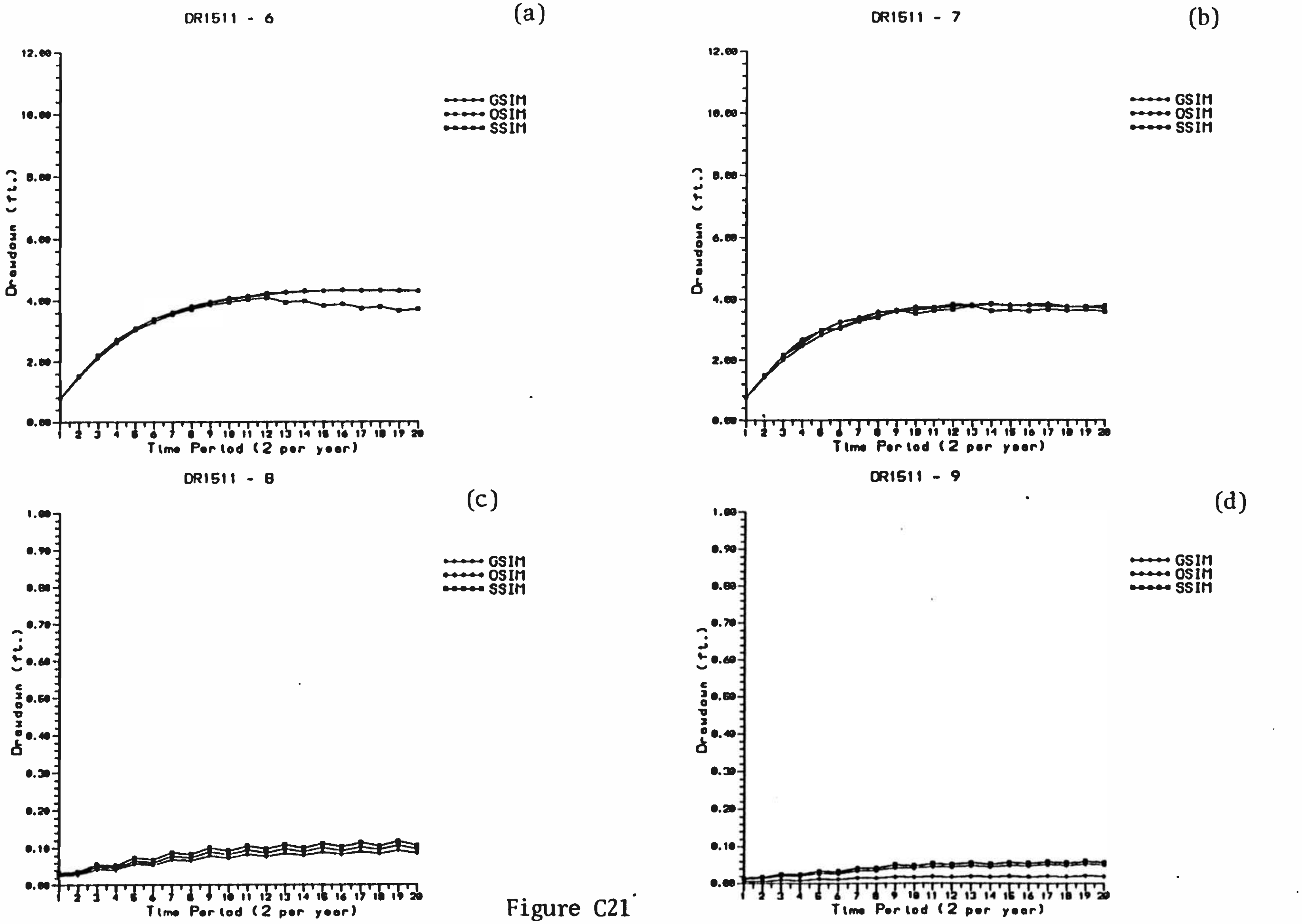

DR1511 - 4A
(a)
DR1511 - GASP
(b)
DR1511 - 5A
(c)
DR1511 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
0.00
2.00
4.00
6.00
8.00
10.00
12.00

Figure C20



DR1511 - 6
(a)
DR1511 - 7
(b)
DR1511 - 8
(c)
DR1511 - 9
(d)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C21

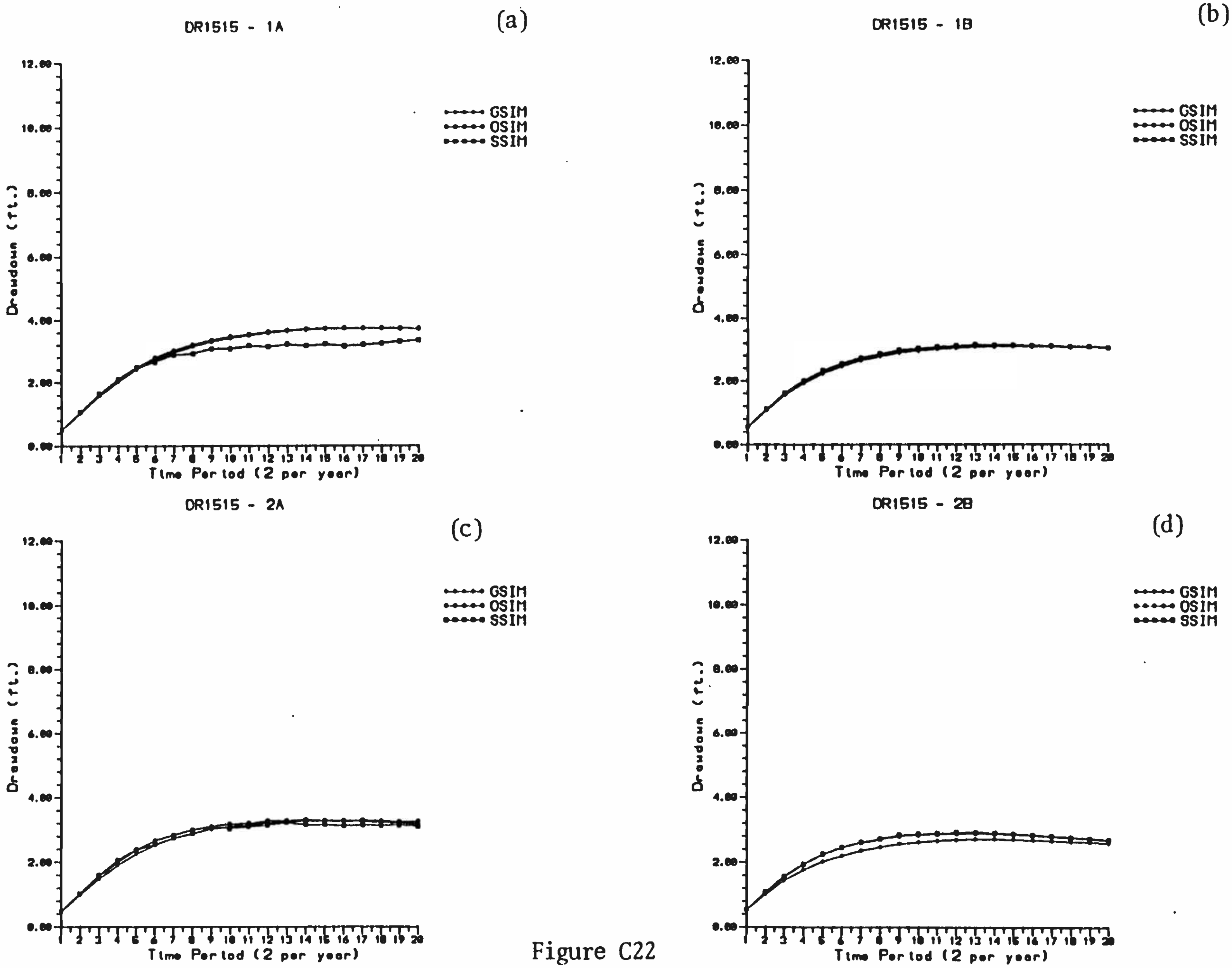

DR1515 - 1A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1515 - 1B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1515 - 2A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1515 - 2B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C22

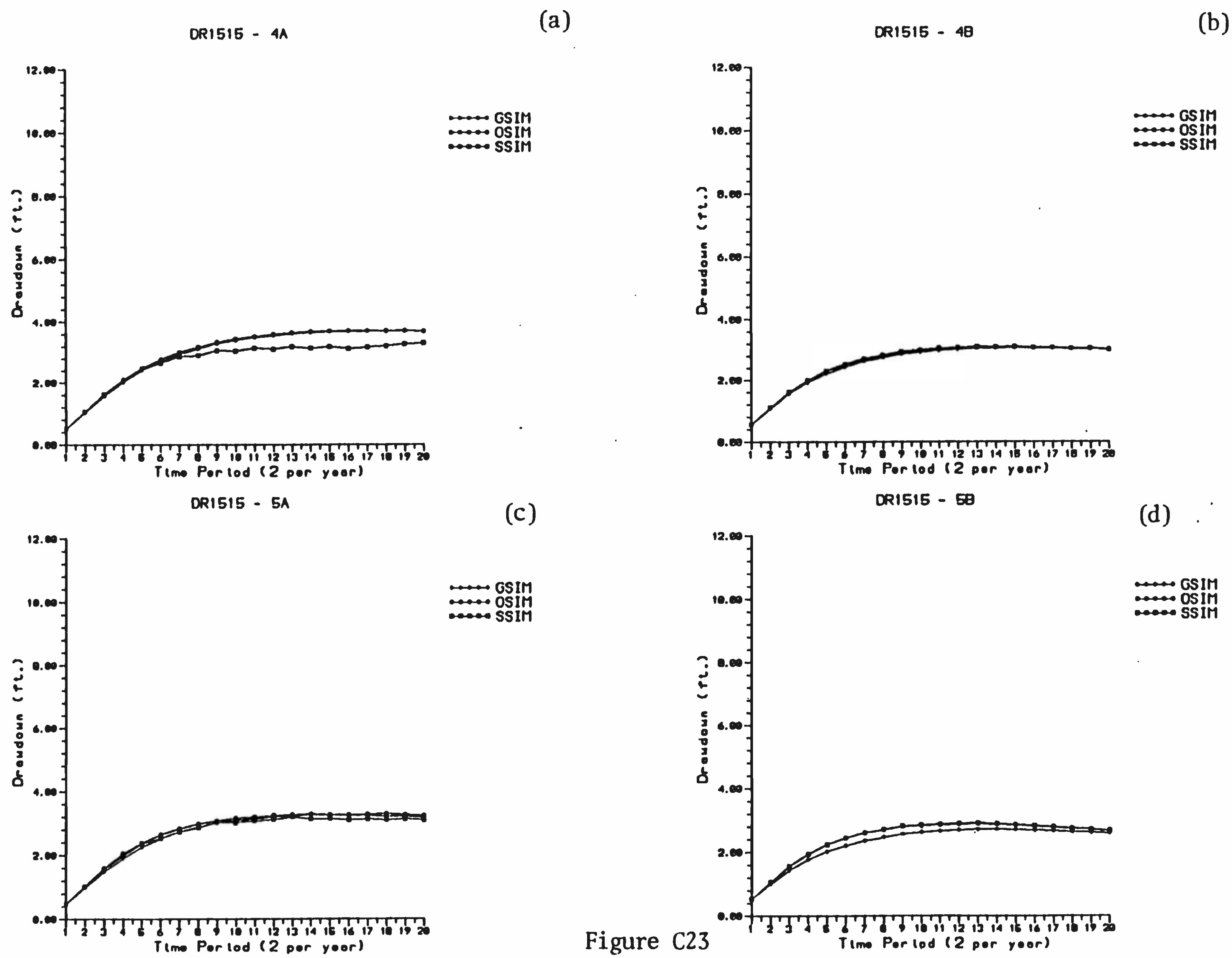

(a)
DR1515 - 4A
(b)
DR1515 - 4B
(c)
DR1515 - 5A
(d)
DR1515 - 5B
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
0.00
2.00
4.00
6.00
8.00
10.00
12.00

Figure C23

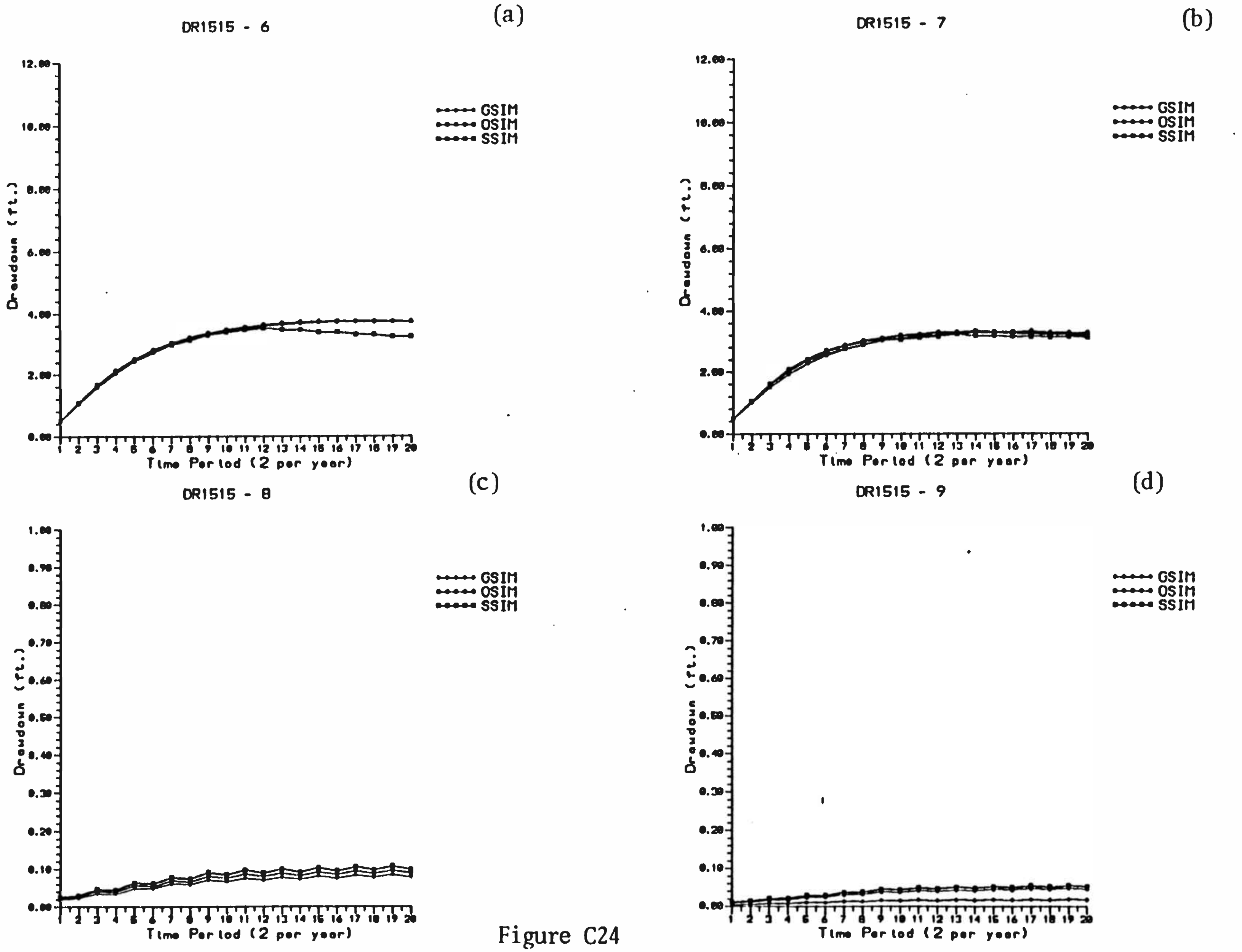

(a)
DR1515 - 6
(b)
DR1515 - 7
(c)
DR1515 - 8
(d)
DR1515 - 9
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C24

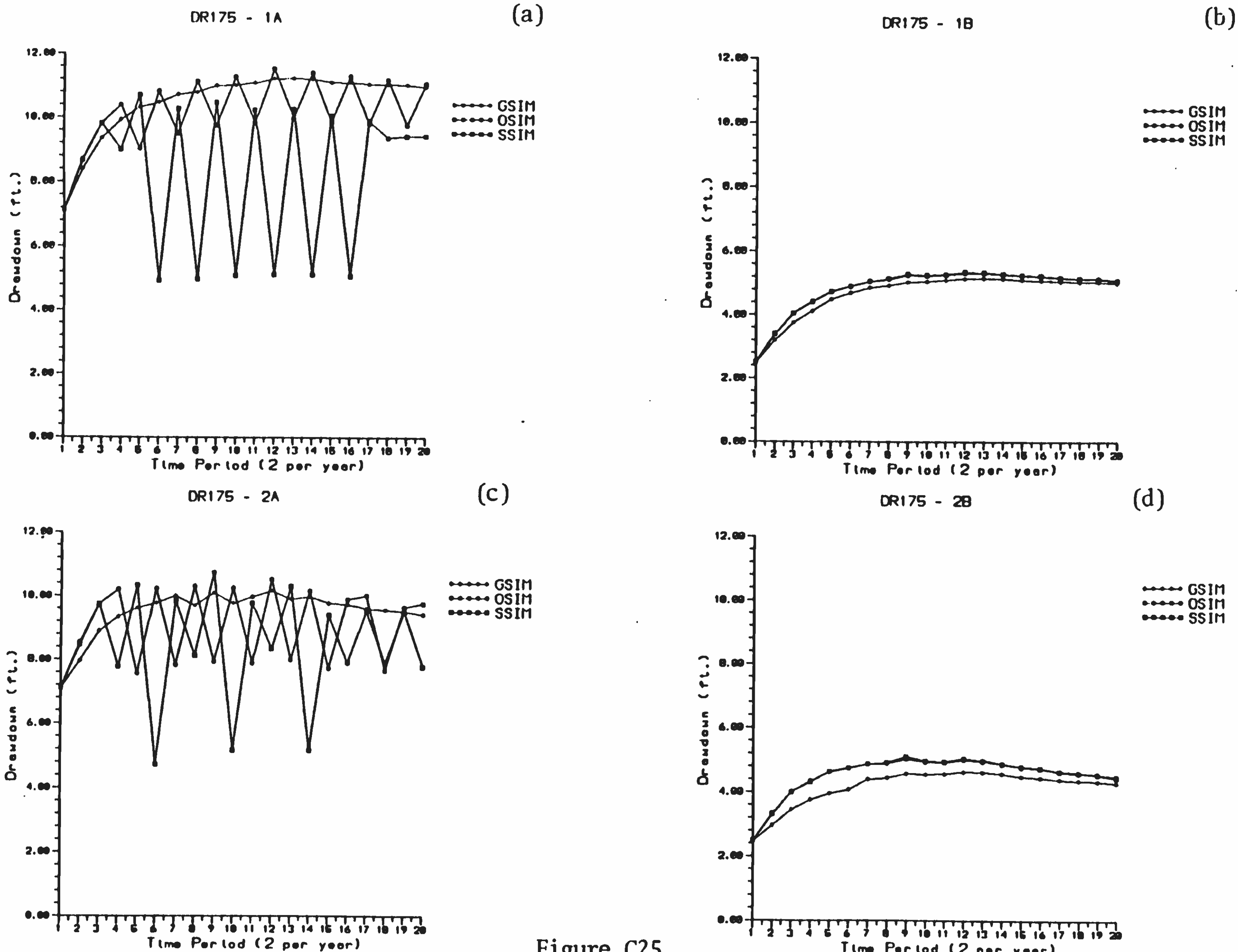

DR175 - 1A
(a)
DR175 - 1B
(b)
DR175 - 2A
(c)
DR175 - 2B
(d)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C25

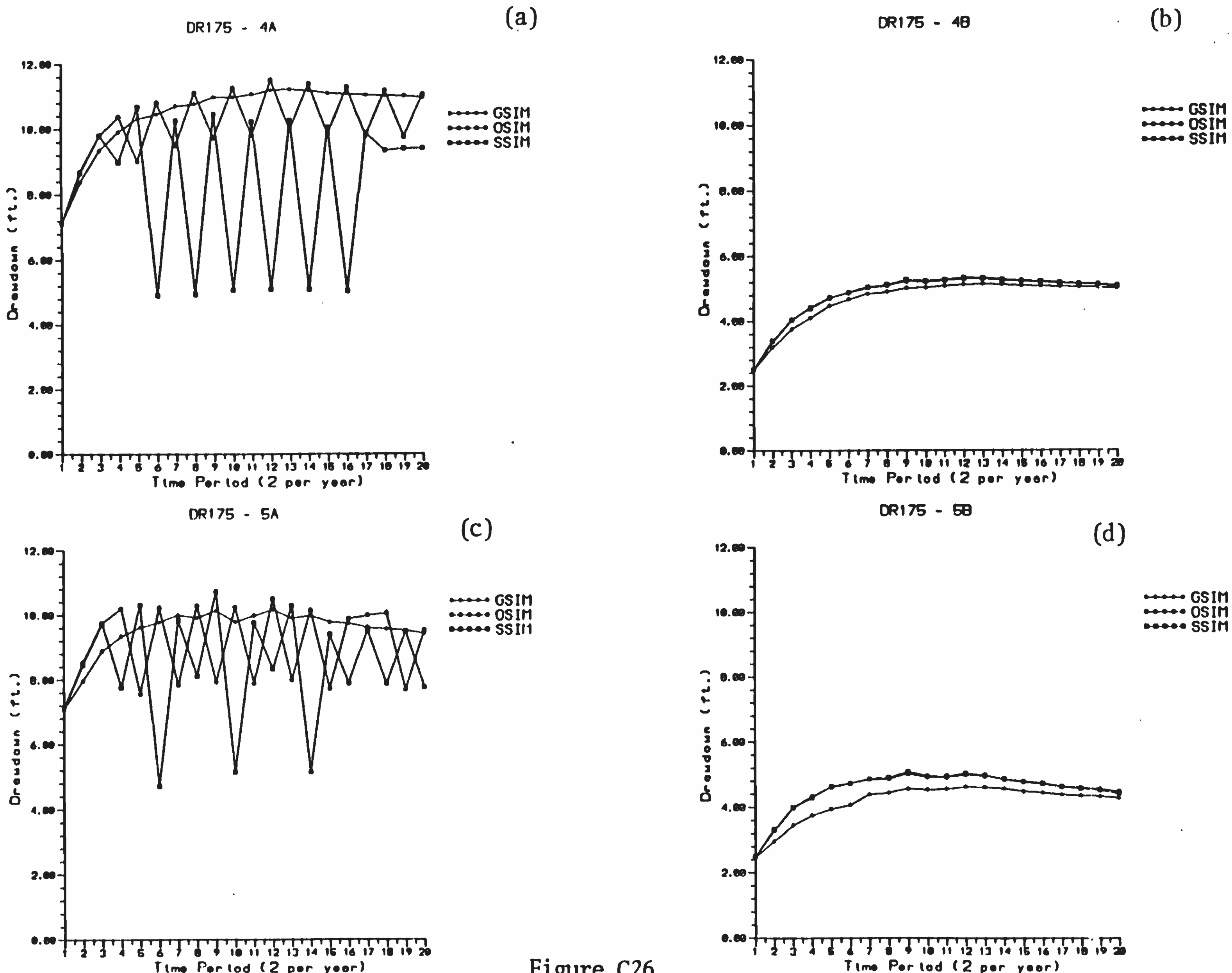

(a)
DR175 - 4A
(b)
DR175 - 4B
(c)
DR175 - 5A
(d)
DR175 - 5B
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
0.00
2.00
4.00
6.00
8.00
10.00
12.00

Figure C26

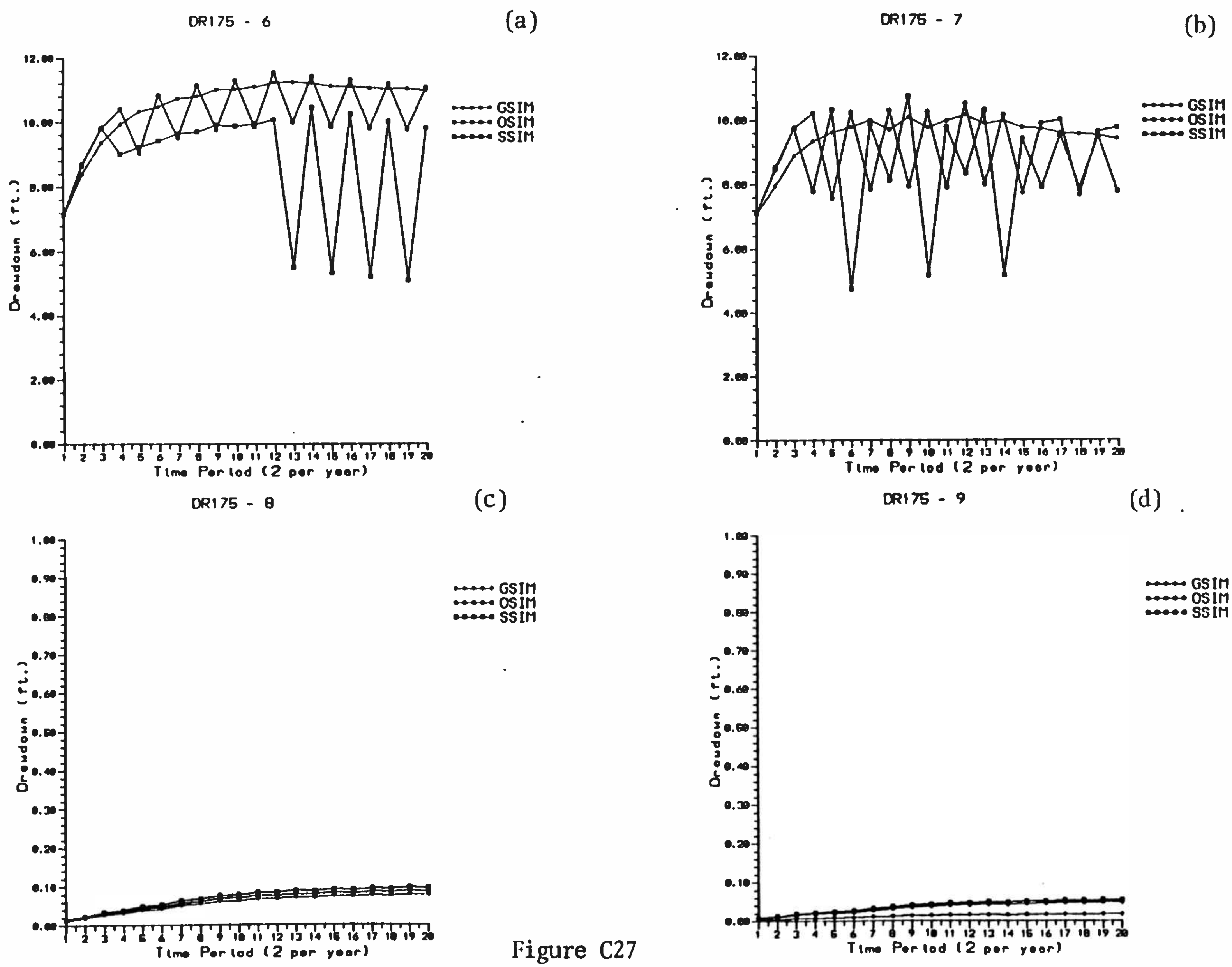

DR175 - 6
(a)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Drawdown (ft.)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
DR175 - 7
(b)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Drawdown (ft.)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
DR175 - 8
(c)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Drawdown (ft.)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
DR175 - 9
(d)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Drawdown (ft.)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C27

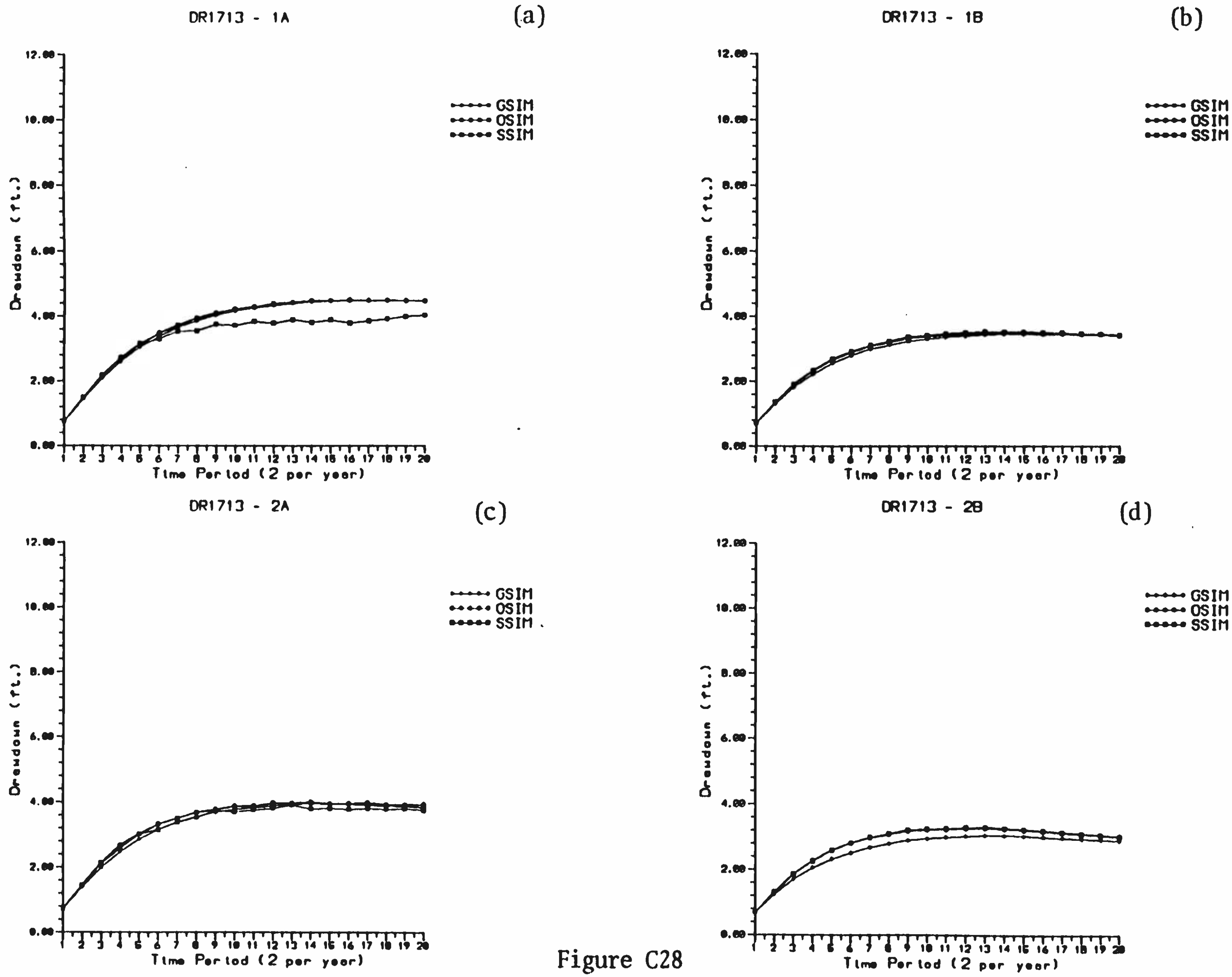
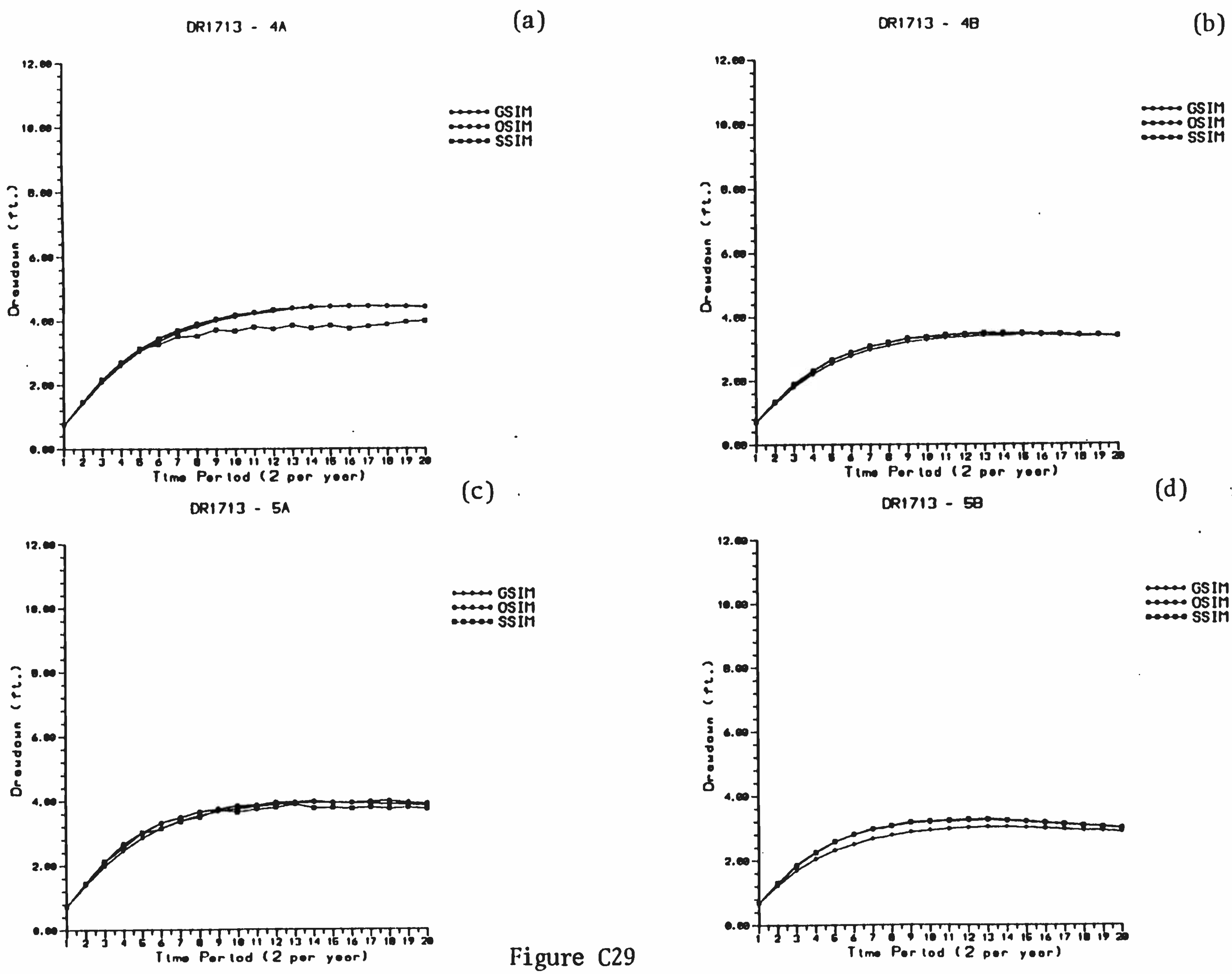

DR1713 - 1A
(a)
DR1713 - 1B
(b)
DR1713 - 2A
(c)
DR1713 - 2B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure C28



(a)
DR1713 - 4A
(b)
DR1713 - 4B
(c)
DR1713 - 5A
(d)
DR1713 - 5B
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure C29

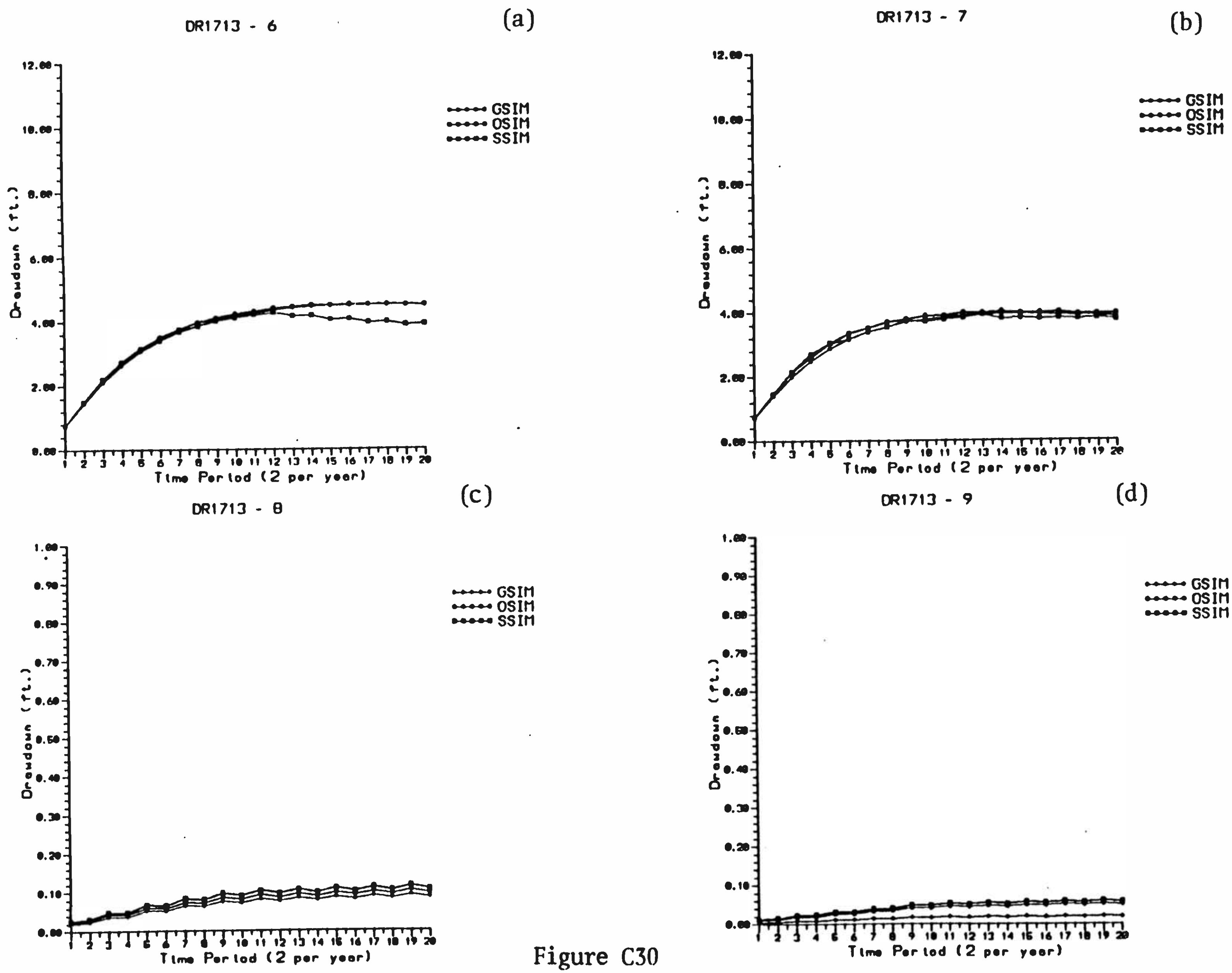

DR1713 - 6
(a)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR1713 - 7
(b)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR1713 - 8
(c)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR1713 - 9
(d)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C30

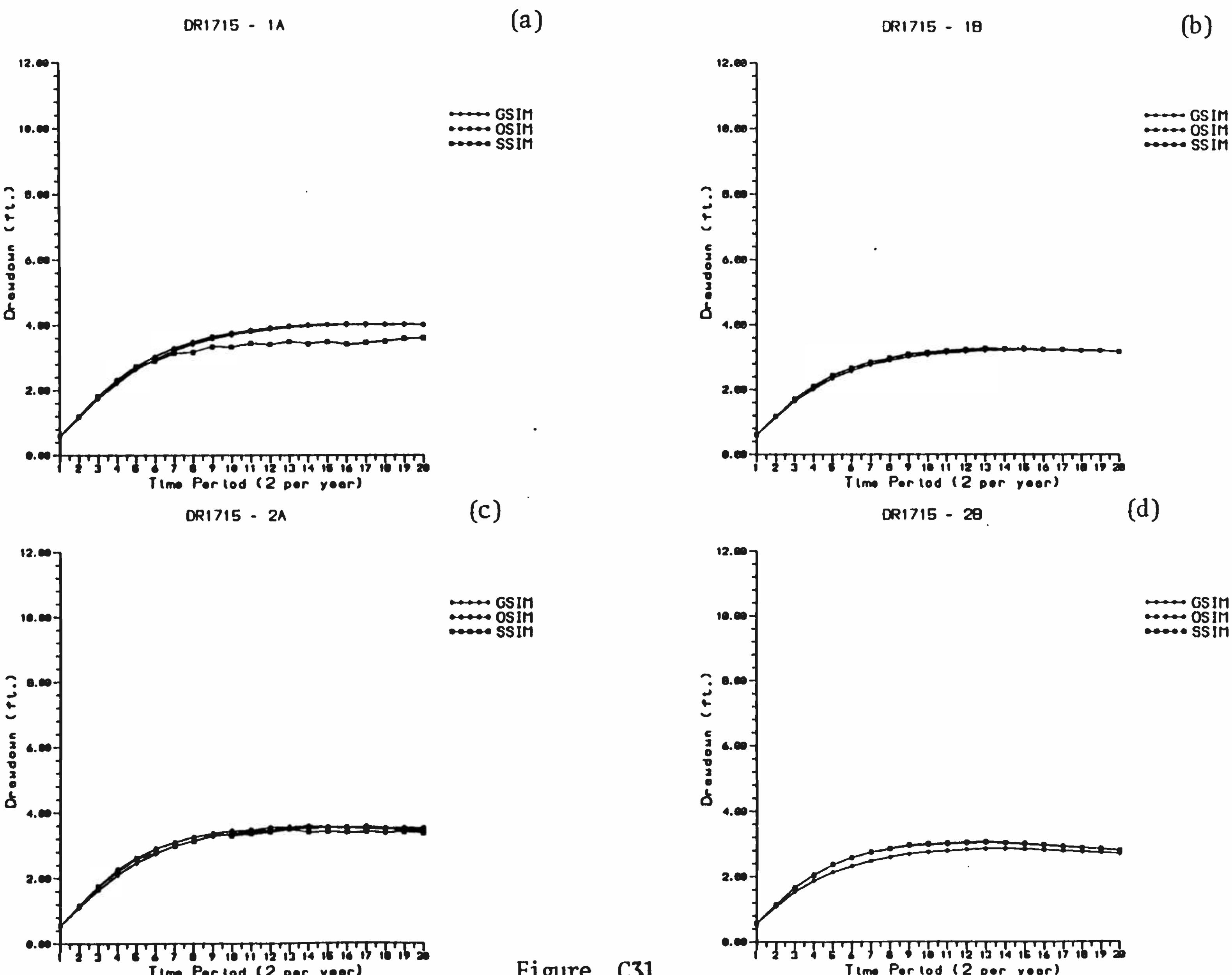

(a)
DR1715 - 1A
(b)
DR1715 - 1B
(c)
DR1715 - 2A
(d)
DR1715 - 2B
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C31

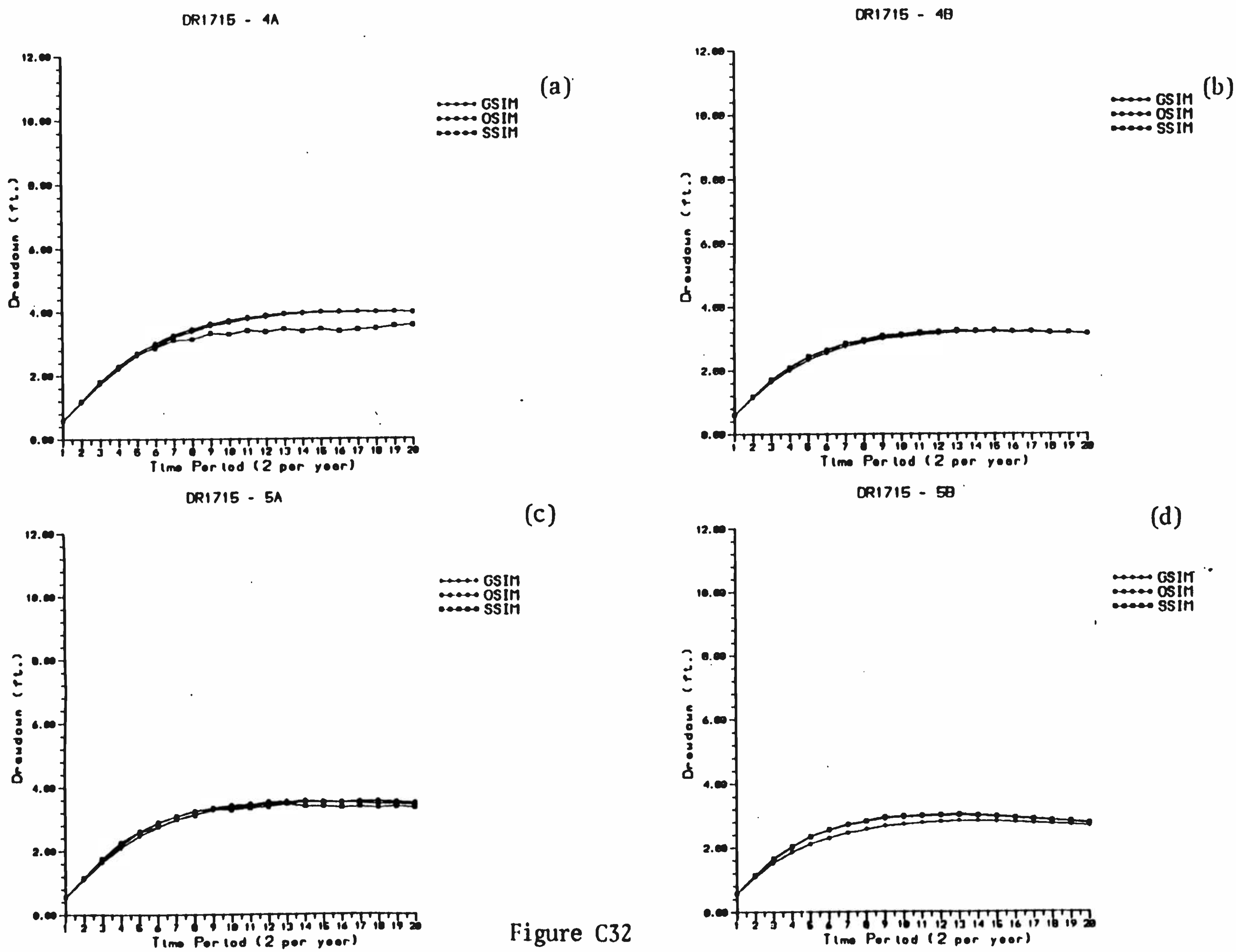
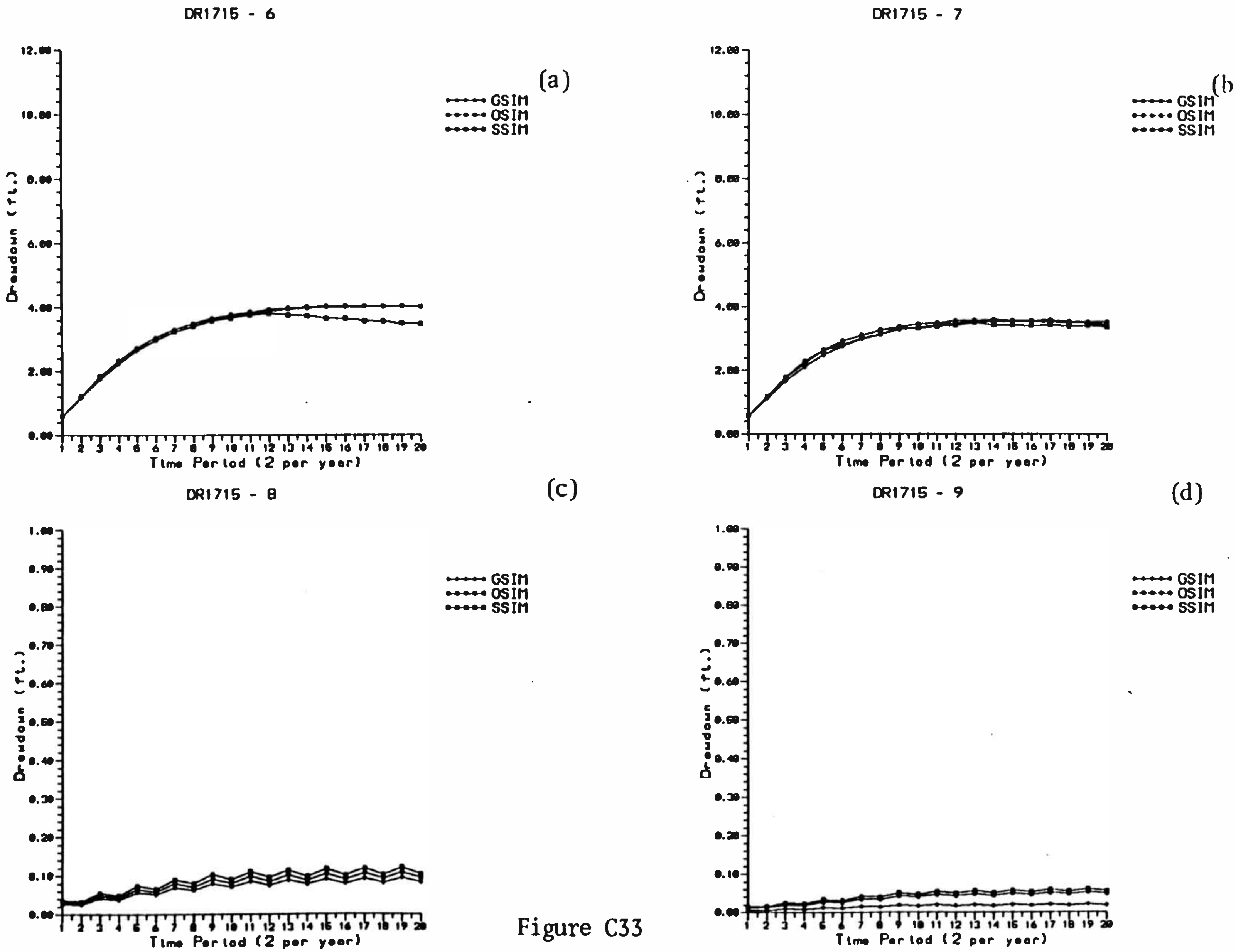
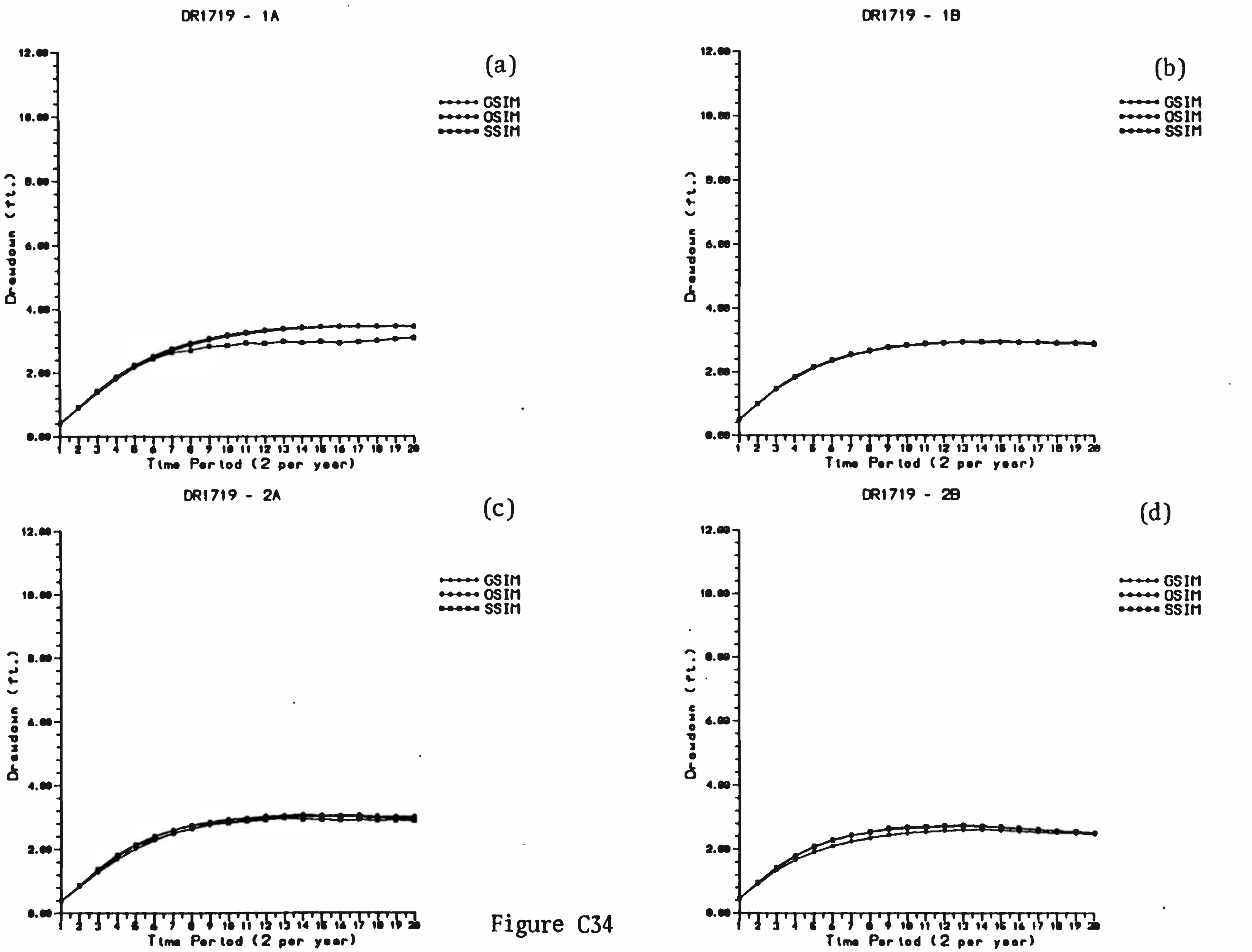

DR1715 - 4A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1715 - 4B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1715 - 5A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1715 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C32



DR1715 - 6
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1715 - 7
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1715 - 8
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1715 - 9
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C33



DR1719 - 1A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1719 - 1B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1719 - 2A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1719 - 2B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C34

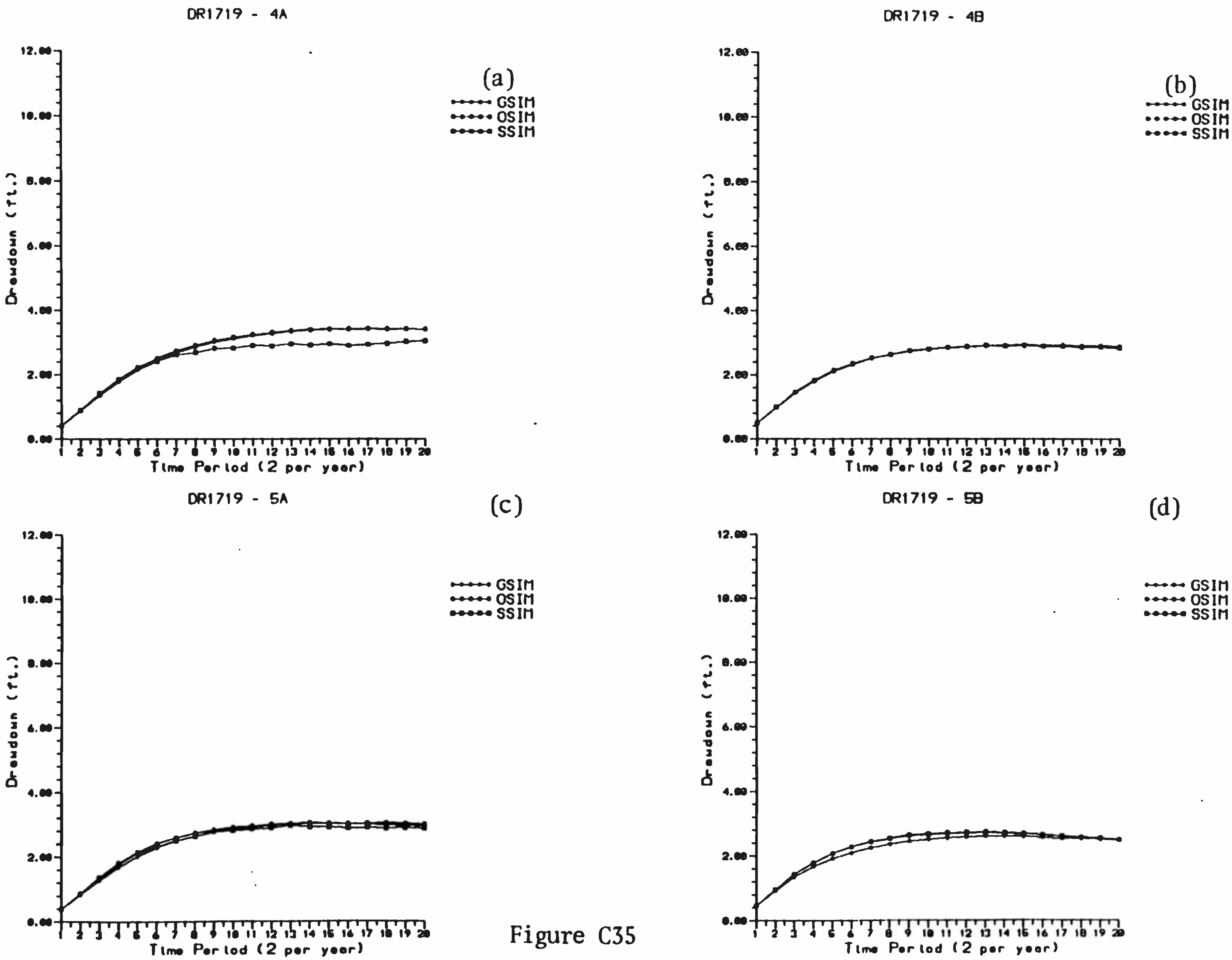

DR1719 - 4A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1719 - 4B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1719 - 5A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1719 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C35

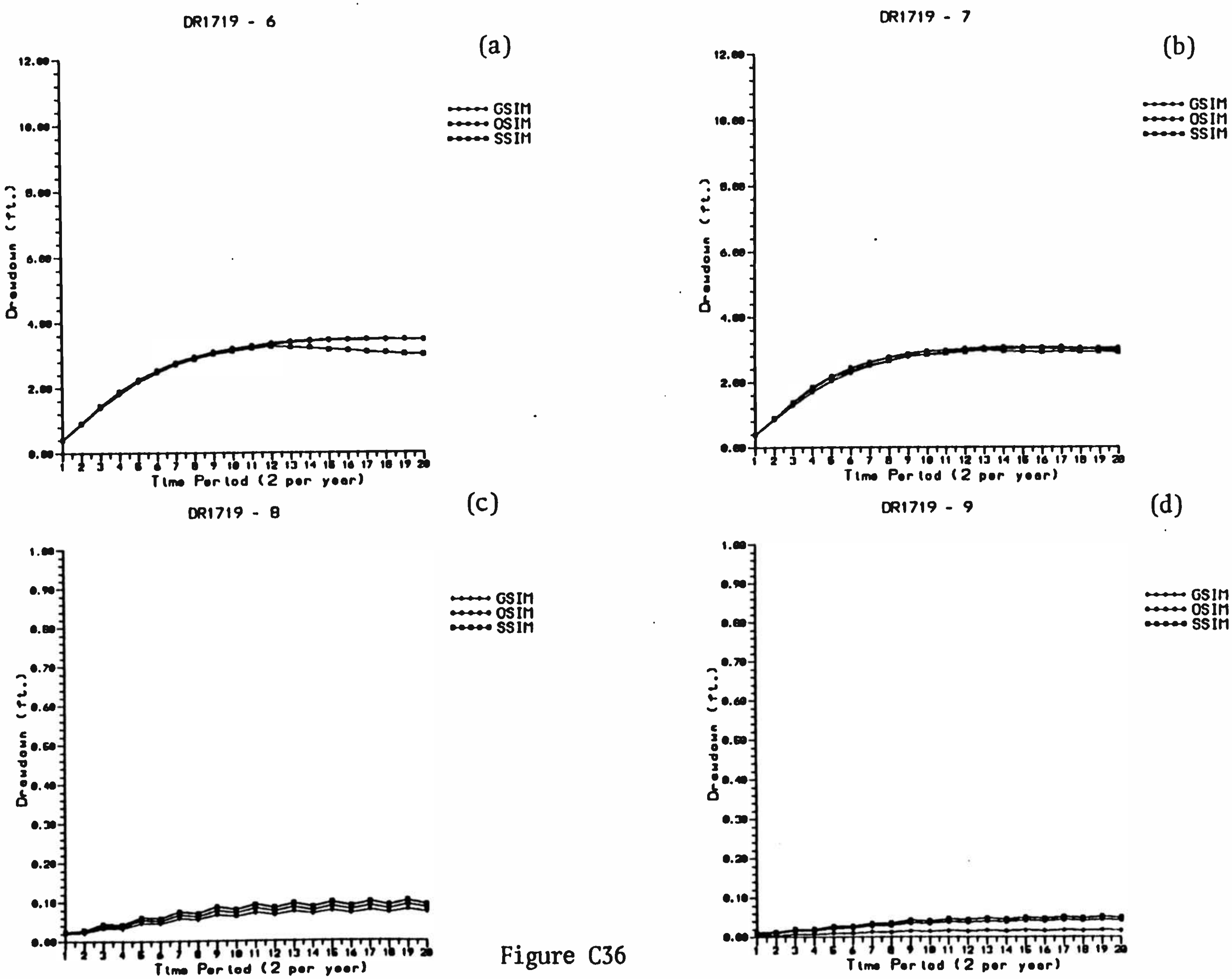

DR1719 - 6
(a)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR1719 - 7
(b)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR1719 - 8
(c)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM
DR1719 - 9
(d)
Drawdown (ft.)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure C36

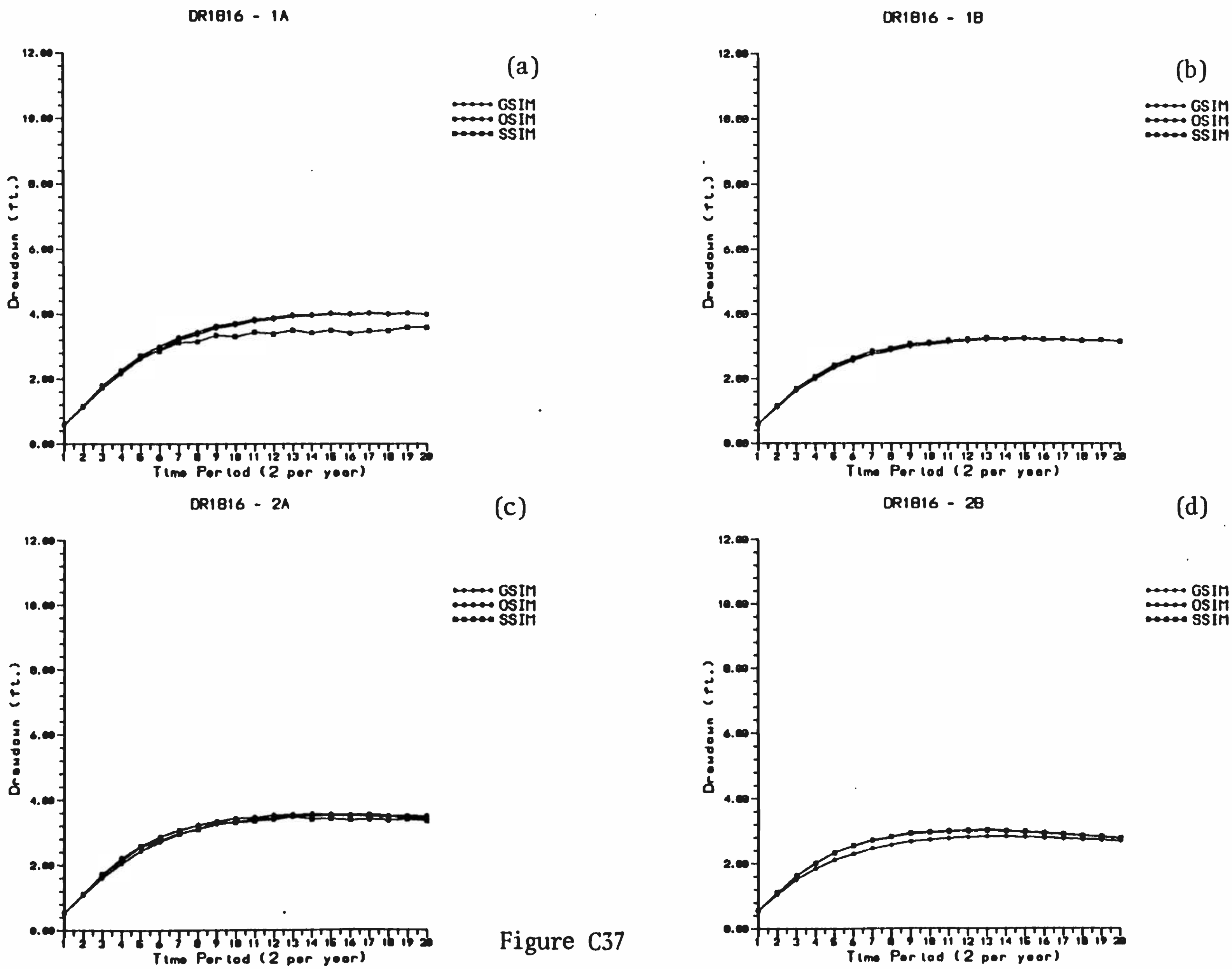

DR1816 - 1A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1816 - 1B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1816 - 2A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1816 - 2B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C37

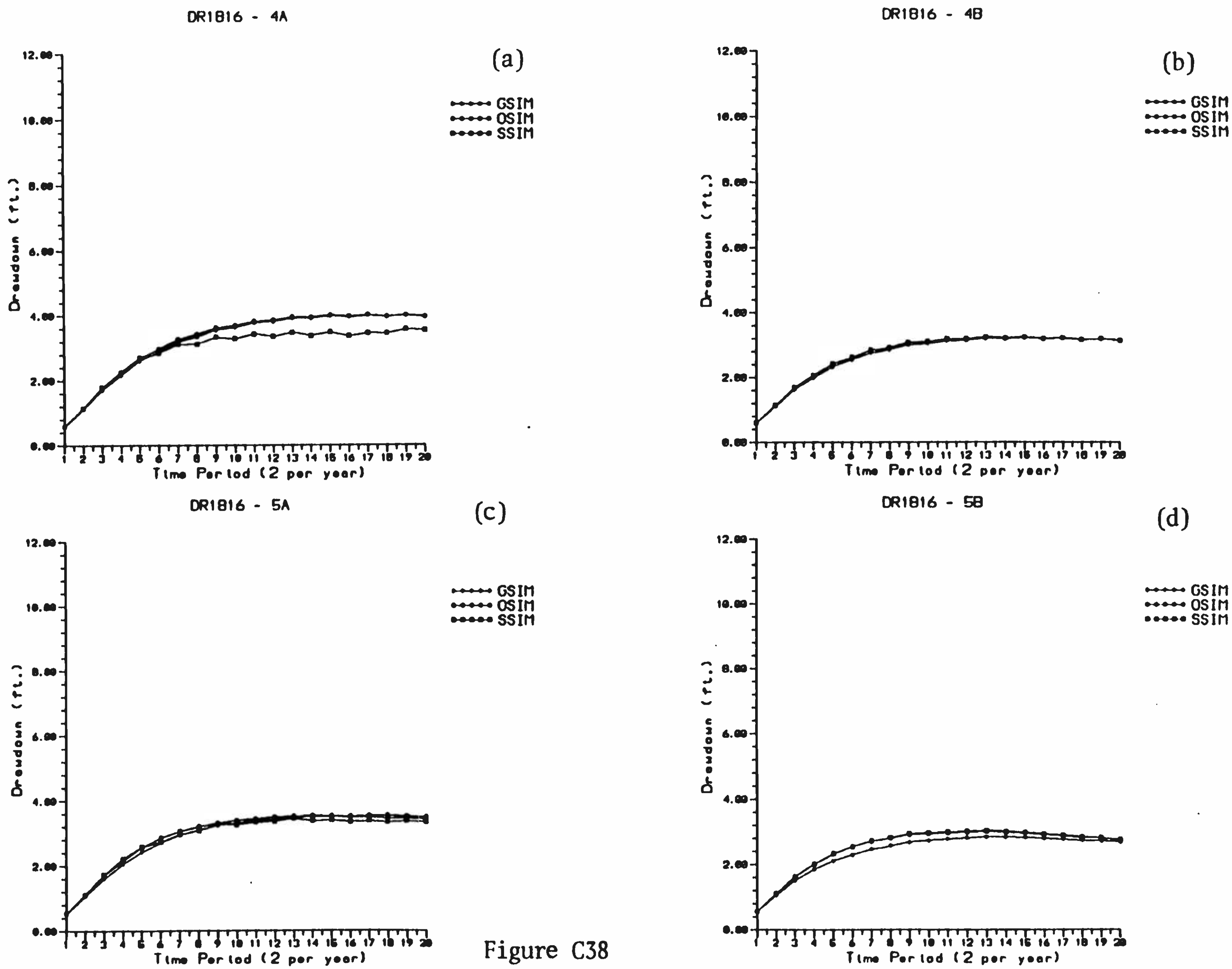
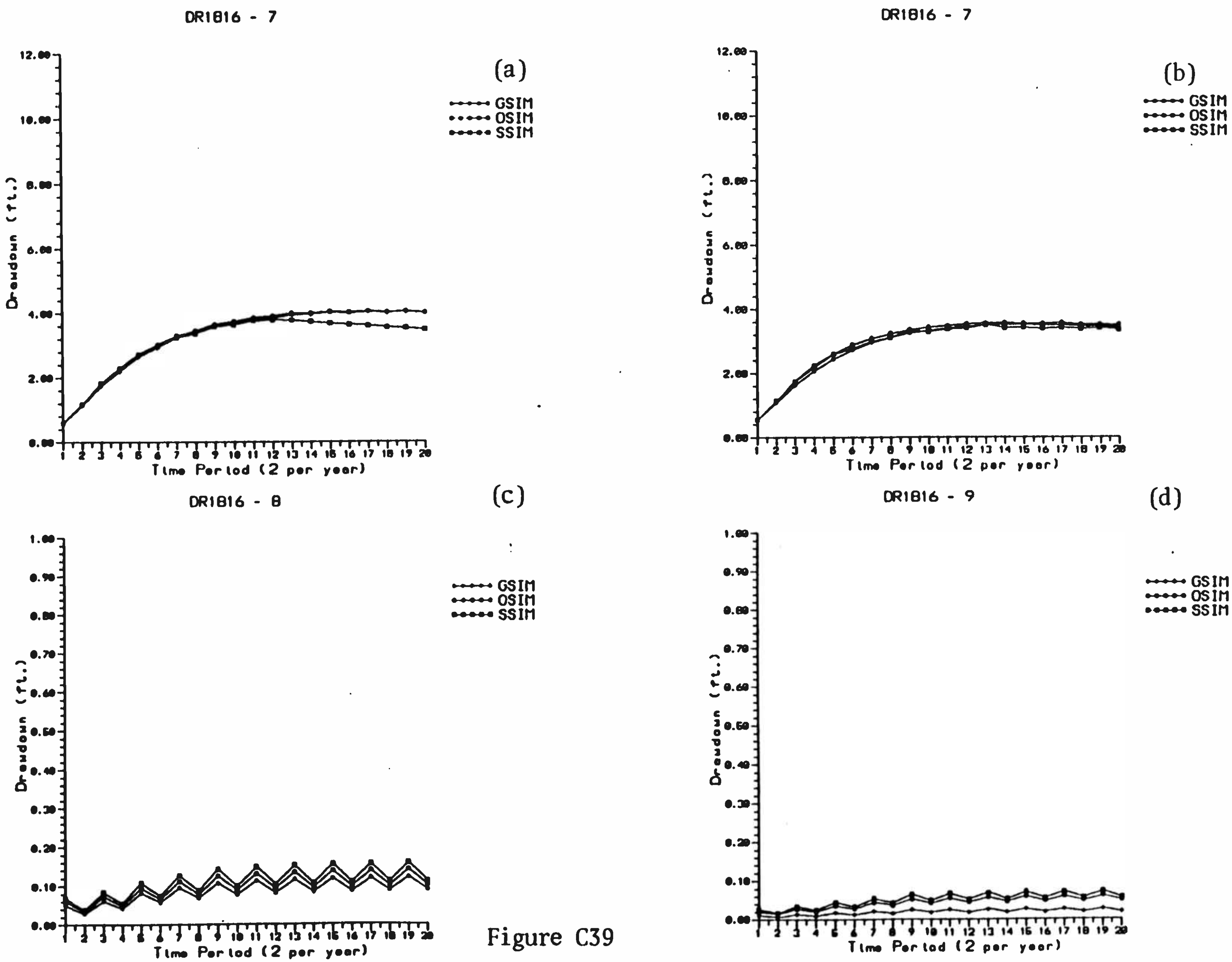
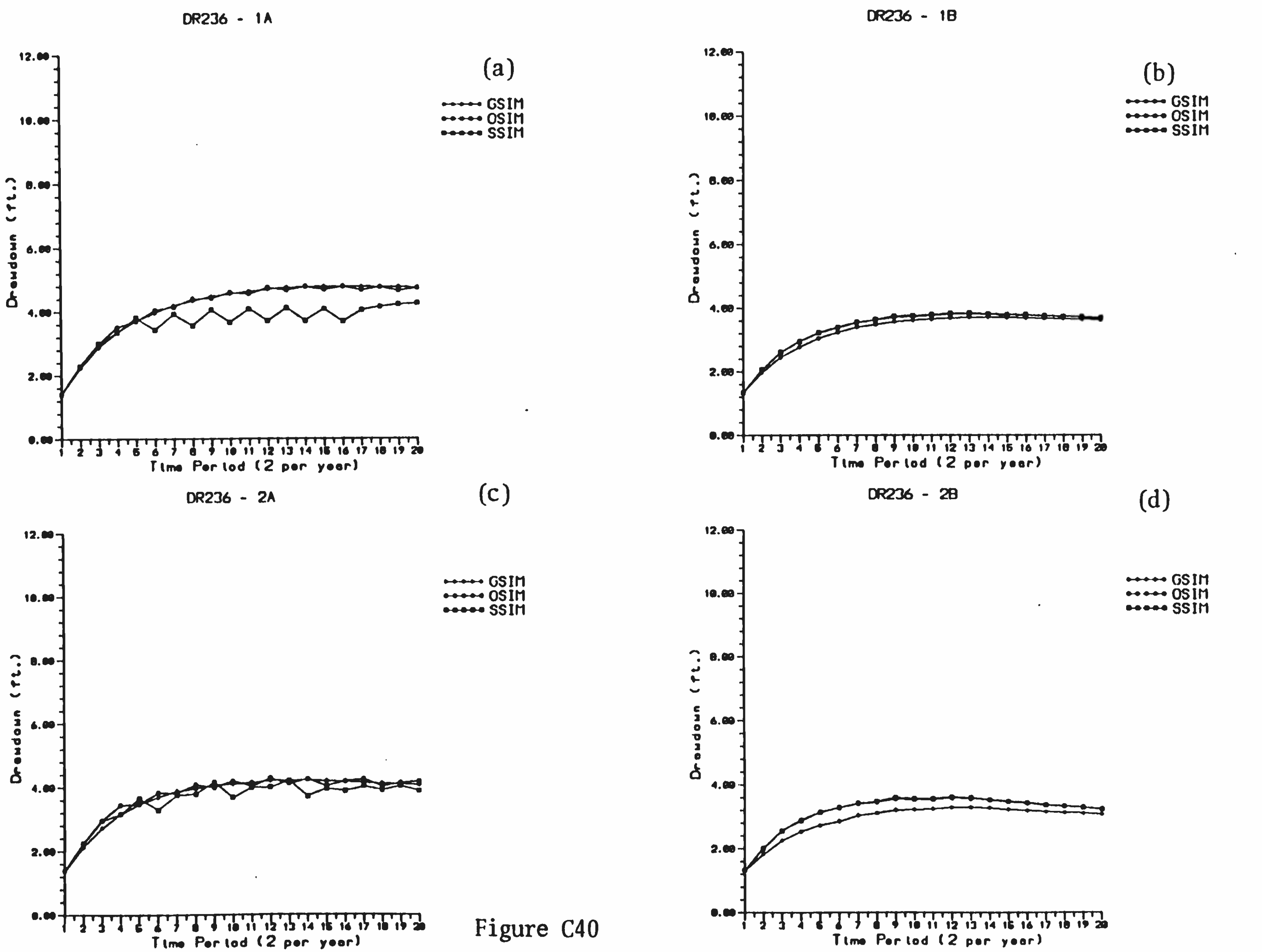

DR1816 - 4A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1816 - 4B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1816 - 5A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1816 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C38



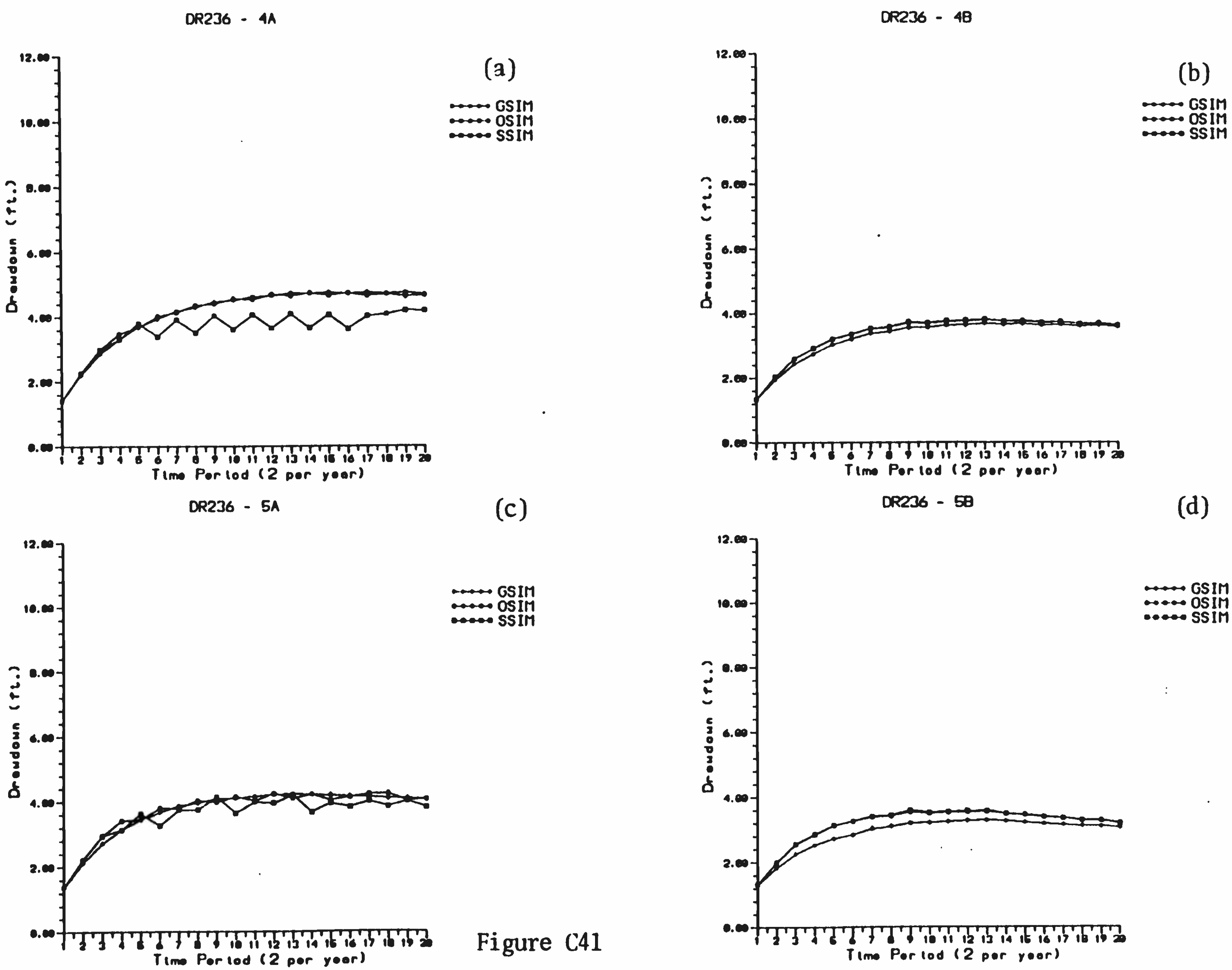
DR1816 - 7
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1816 - 7
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1816 - 8
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR1816 - 9
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C39



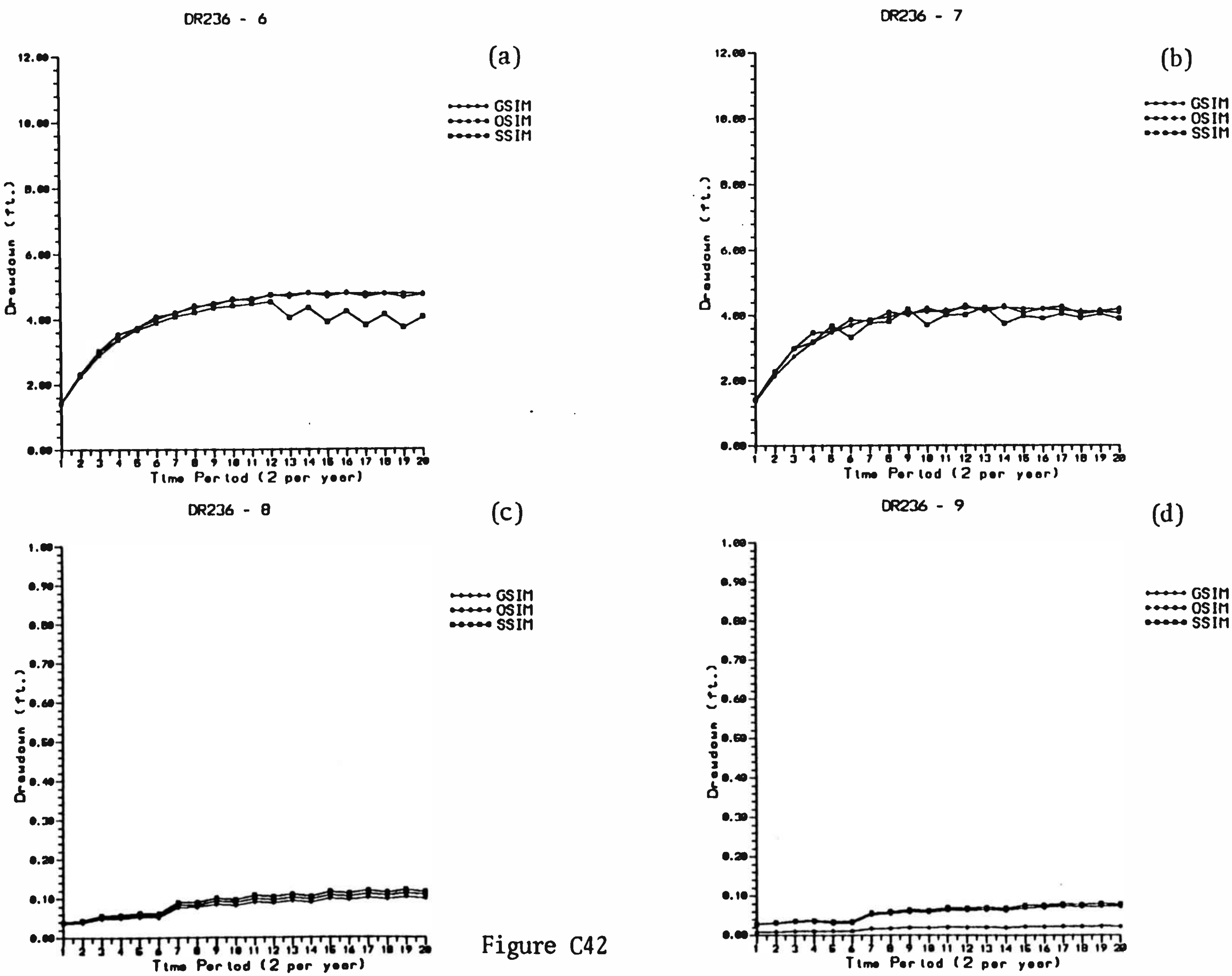
DR236 - 1A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR236 - 1B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR236 - 2A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR236 - 2B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C40



DR236 - 4A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR236 - 4B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR236 - 5A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR236 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C41



DR236 - 6
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR236 - 7
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR236 - 8
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR236 - 9
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C42

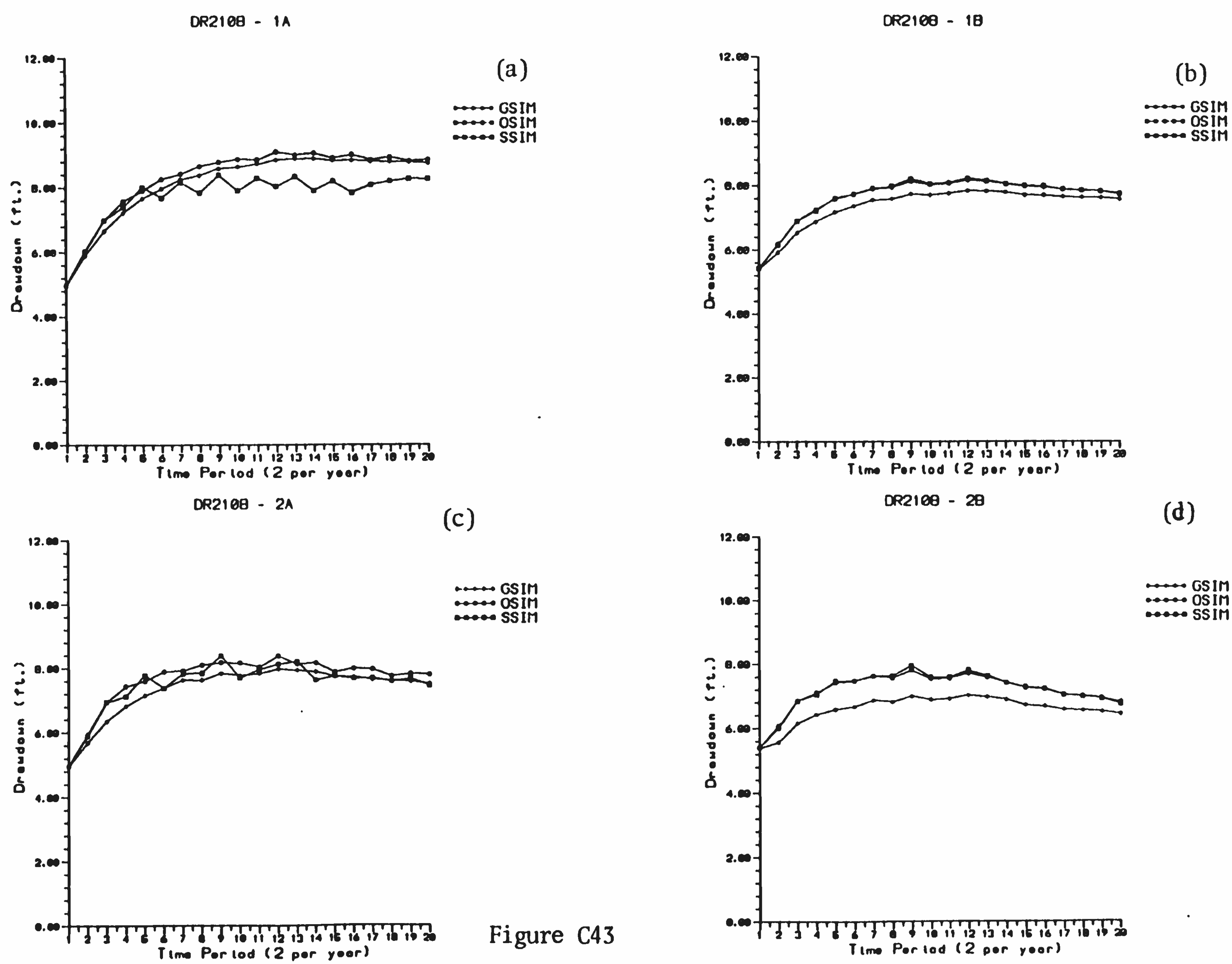

DR2108 - 1A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Time Period (2 per year)
DR2108 - 1B
(b)
GSIM
OSIM
SSIM
DR2108 - 2A
(c)
GSIM
OSIM
SSIM
DR2108 - 2B
(d)
GSIM
OSIM
SSIM

Figure C43

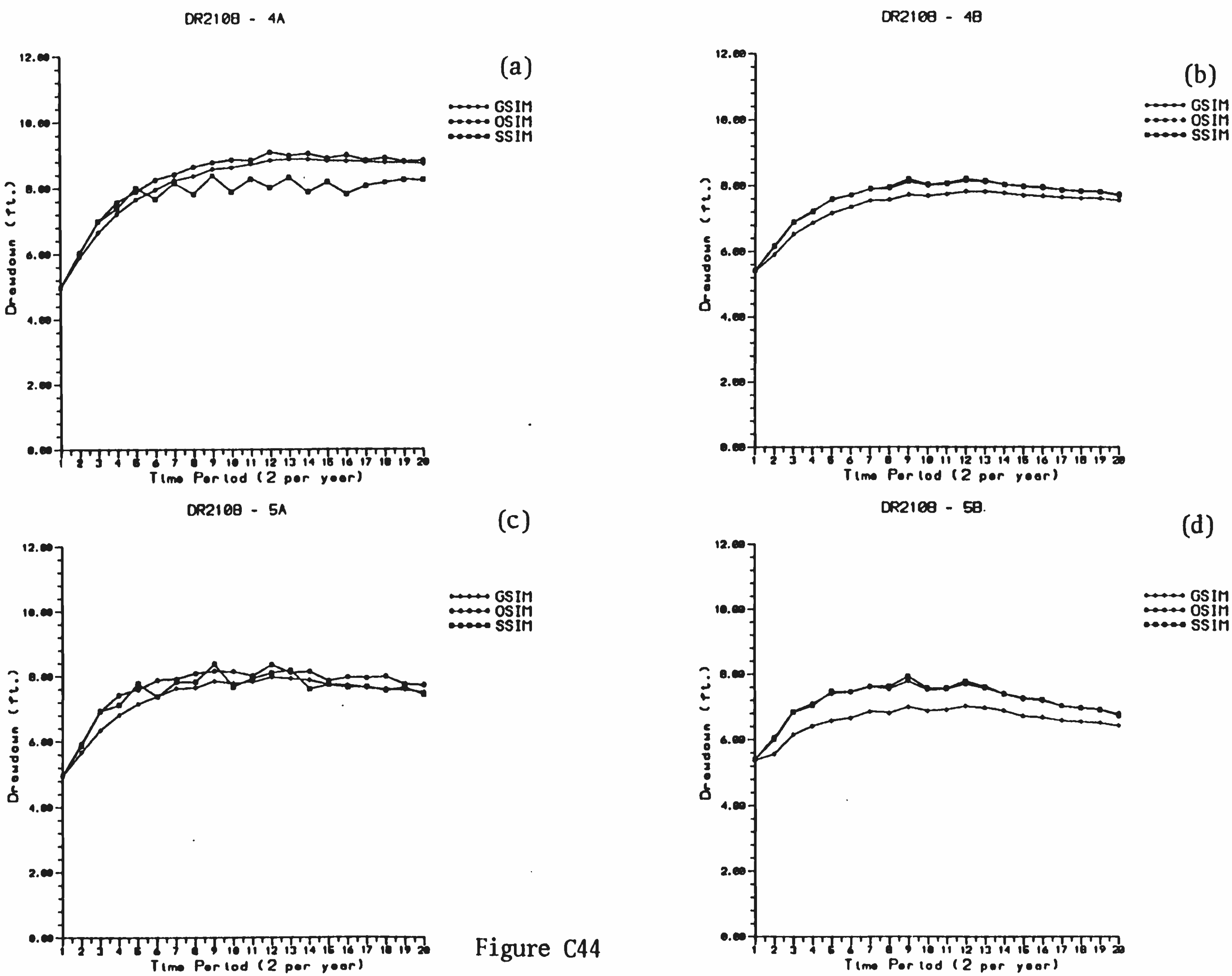

DR2108 - 4A
(a)
DR2108 - 4B
(b)
DR2108 - 5A
(c)
DR2108 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
12.00
10.00
8.00
6.00
4.00
2.00
0.00

Figure C44

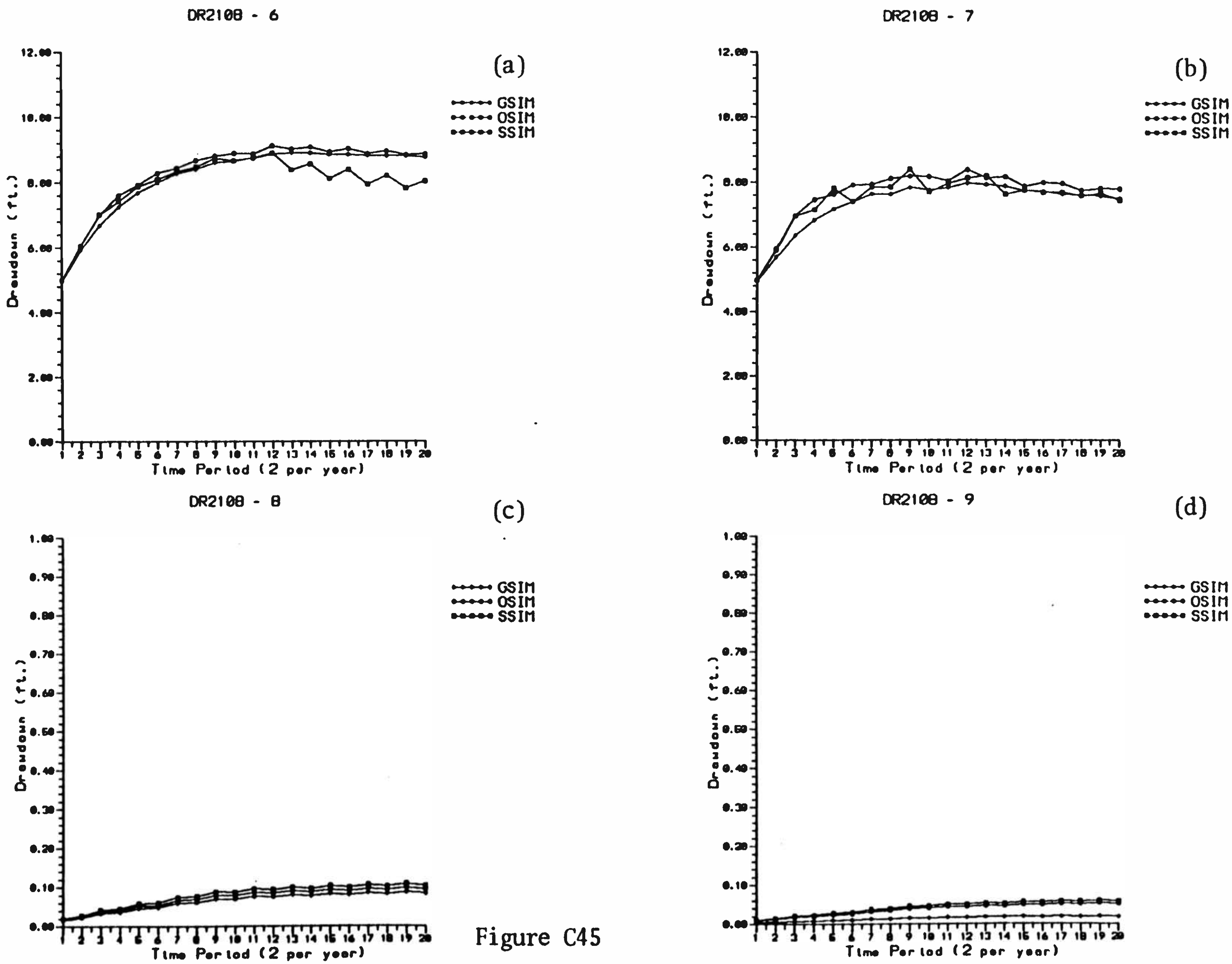

DR2108 - 6
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2108 - 7
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2108 - 8
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2108 - 9
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C45

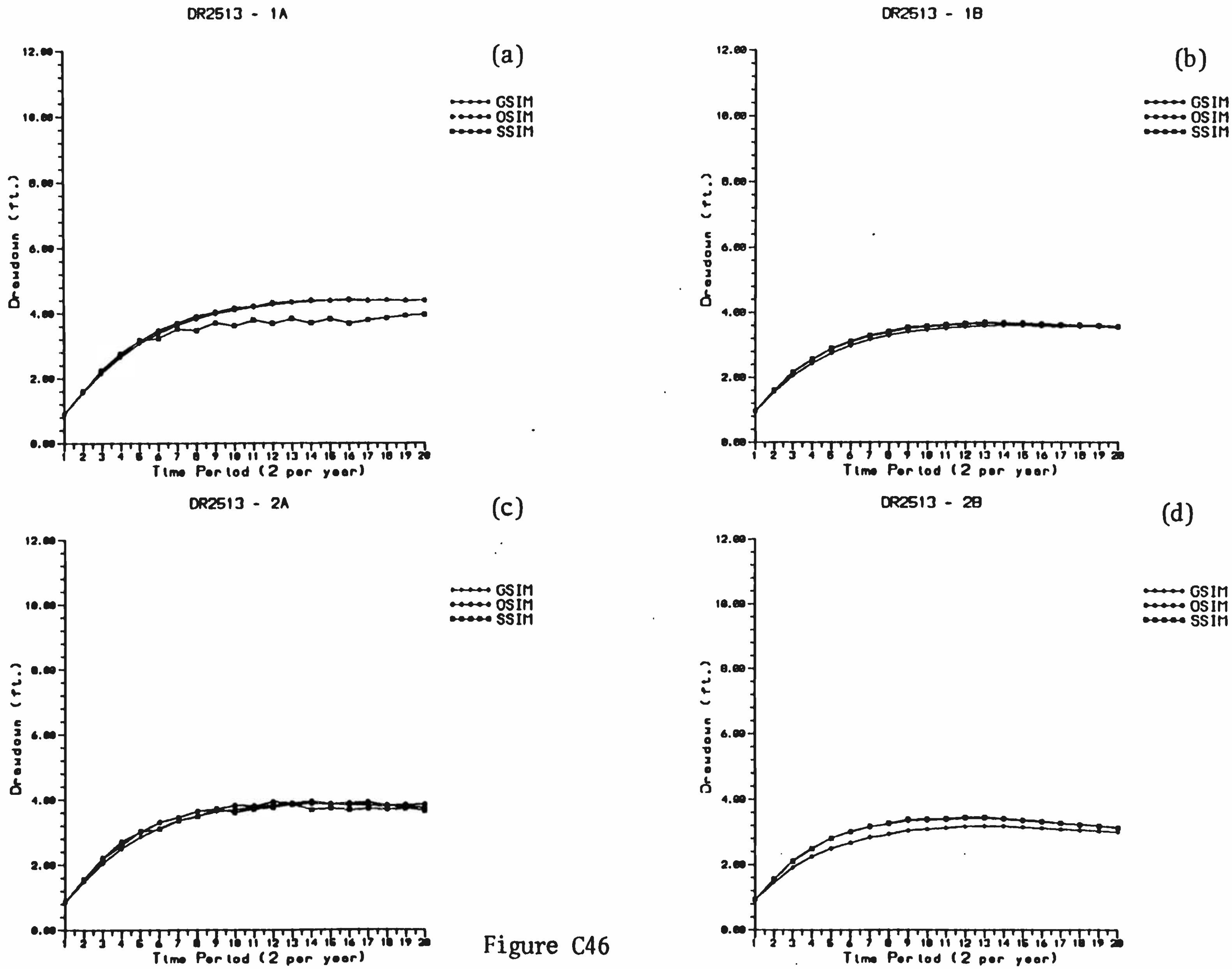

DR2513 - 1A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2513 - 1B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2513 - 2A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2513 - 2B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C46

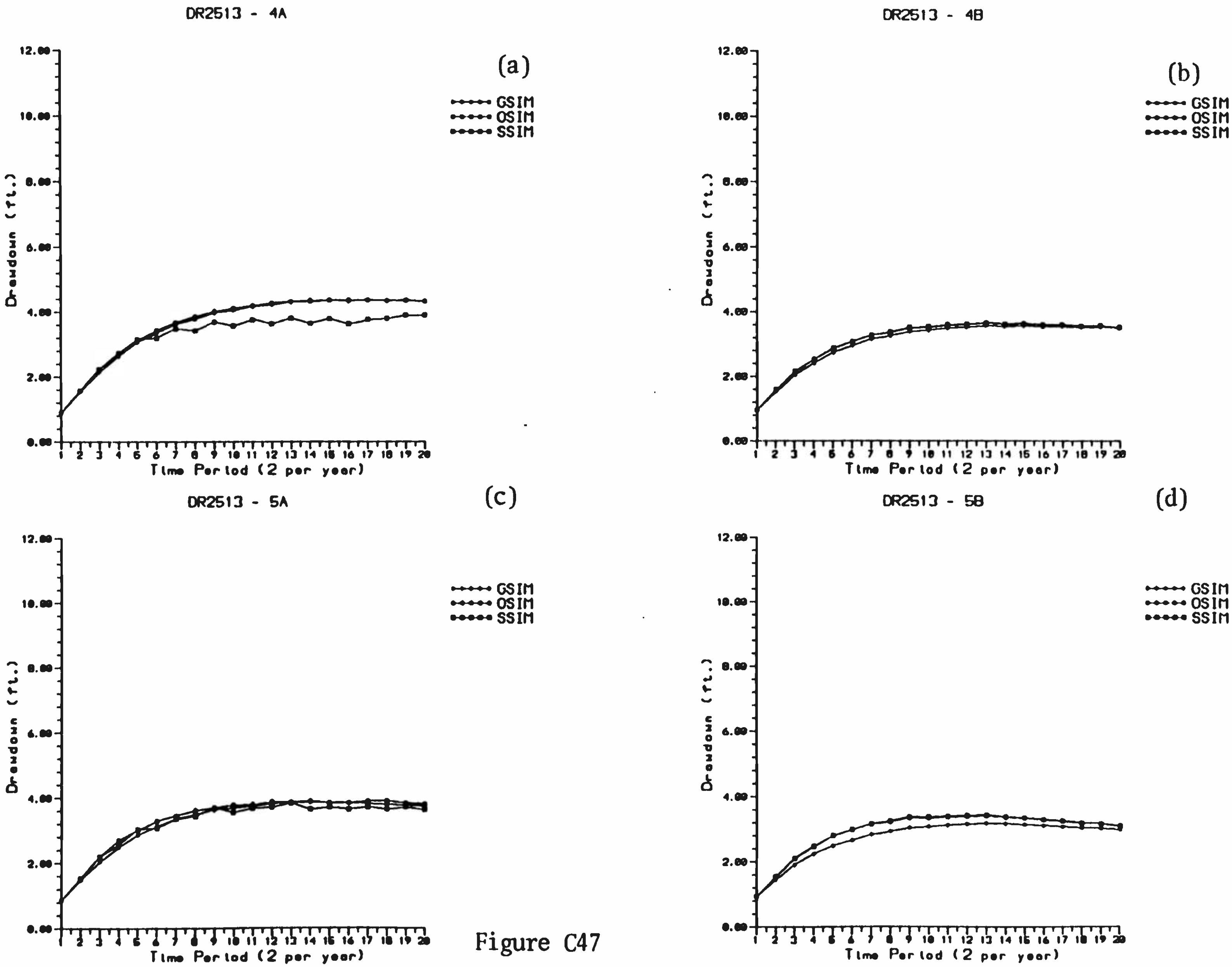

DR2513 - 4A
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2513 - 4B
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2513 - 5A
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2513 - 5B
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C47

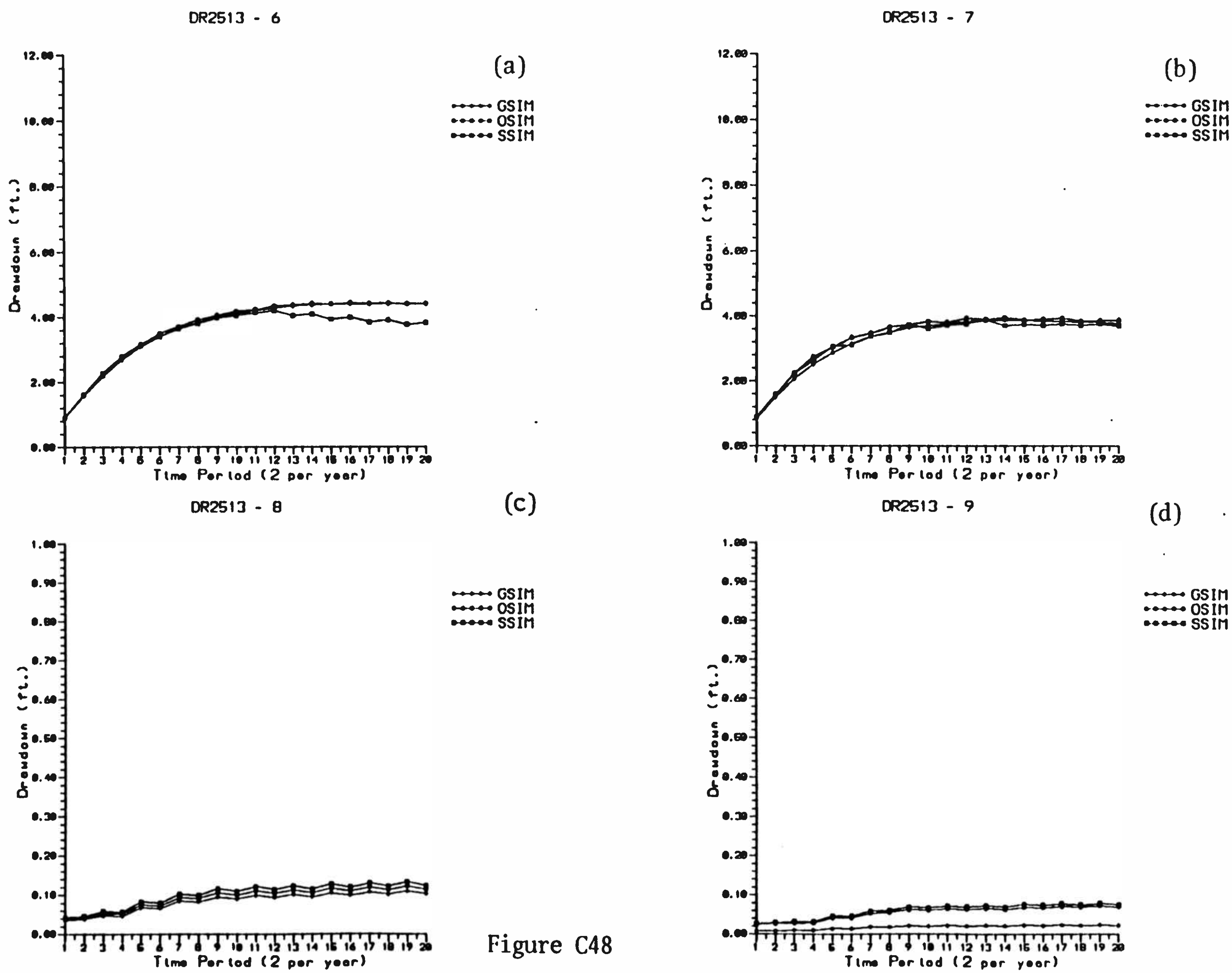
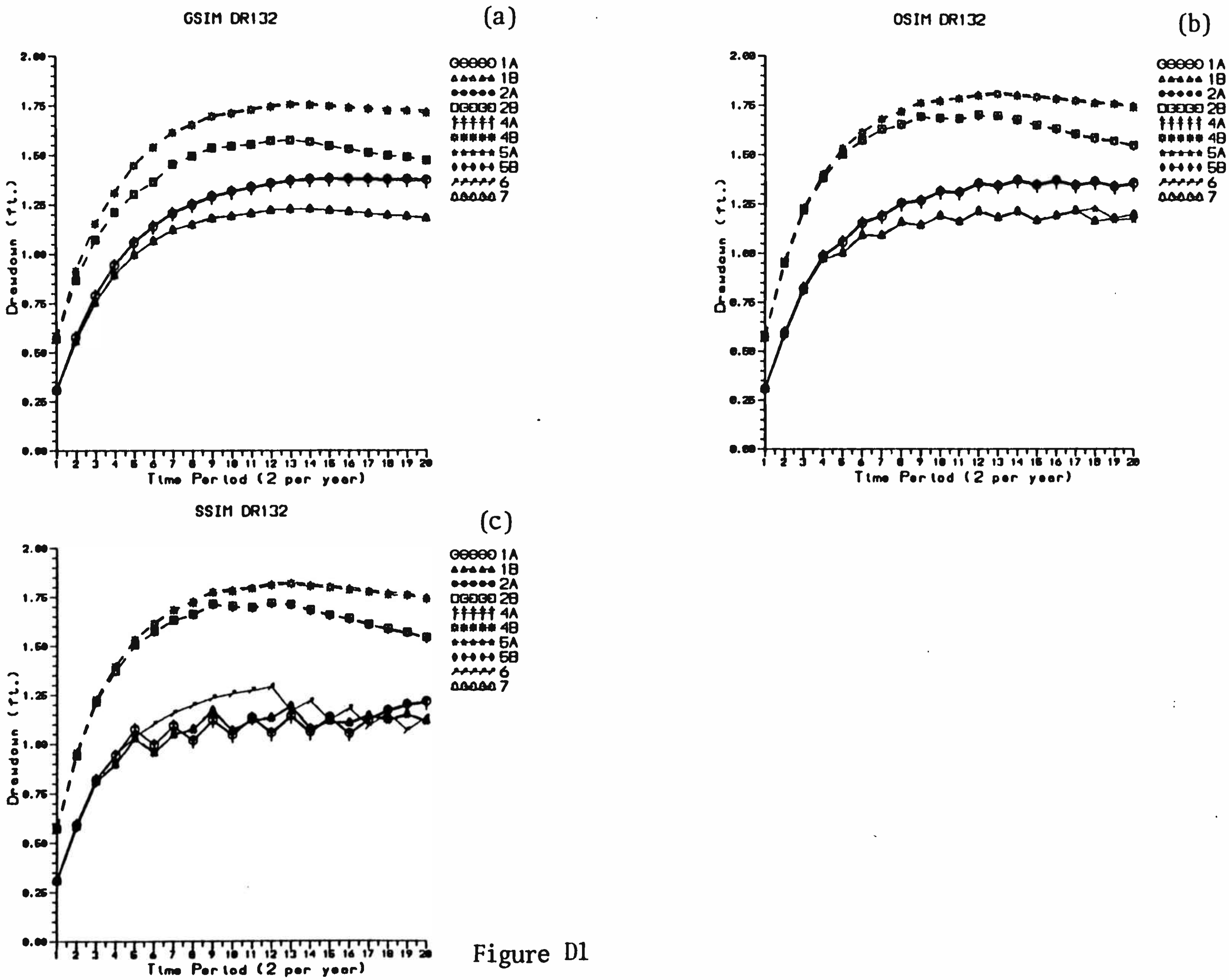

DR2513 - 6
(a)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2513 - 7
(b)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2513 - 8
(c)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)
DR2513 - 9
(d)
GSIM
OSIM
SSIM
Drawdown (ft.)
Time Period (2 per year)

Figure C48

APPENDIX D

Composite Drawdown Plots



GSIM DR132
(a)
OSIM DR132
(b)
SSIM DR132
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D1

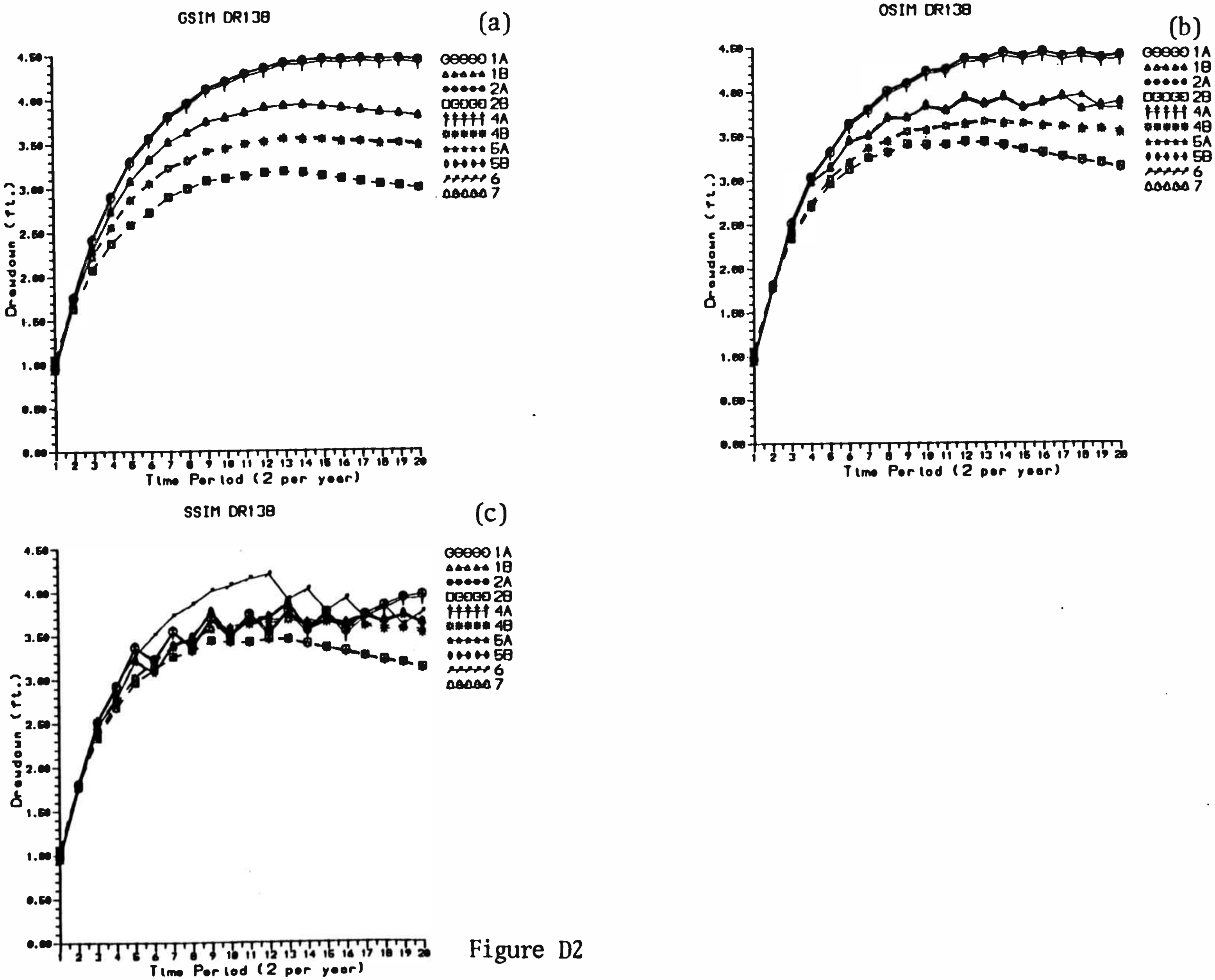

GSIM DR13B
(a)
OSIM DR13B
(b)
SSIM DR13B
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D2

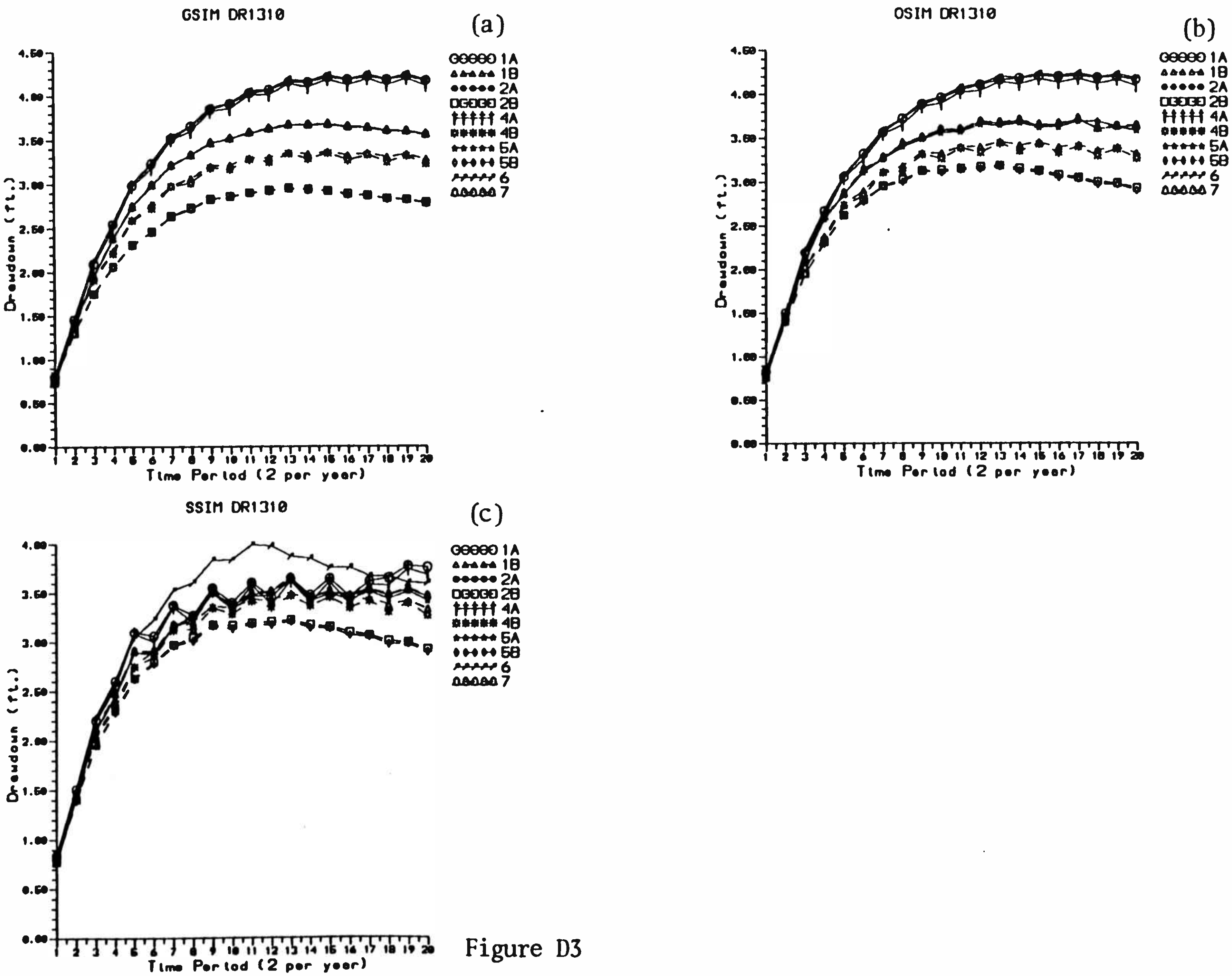

GSIM DR1310
(a)
OSIM DR1310
(b)
SSIM DR1310
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D3

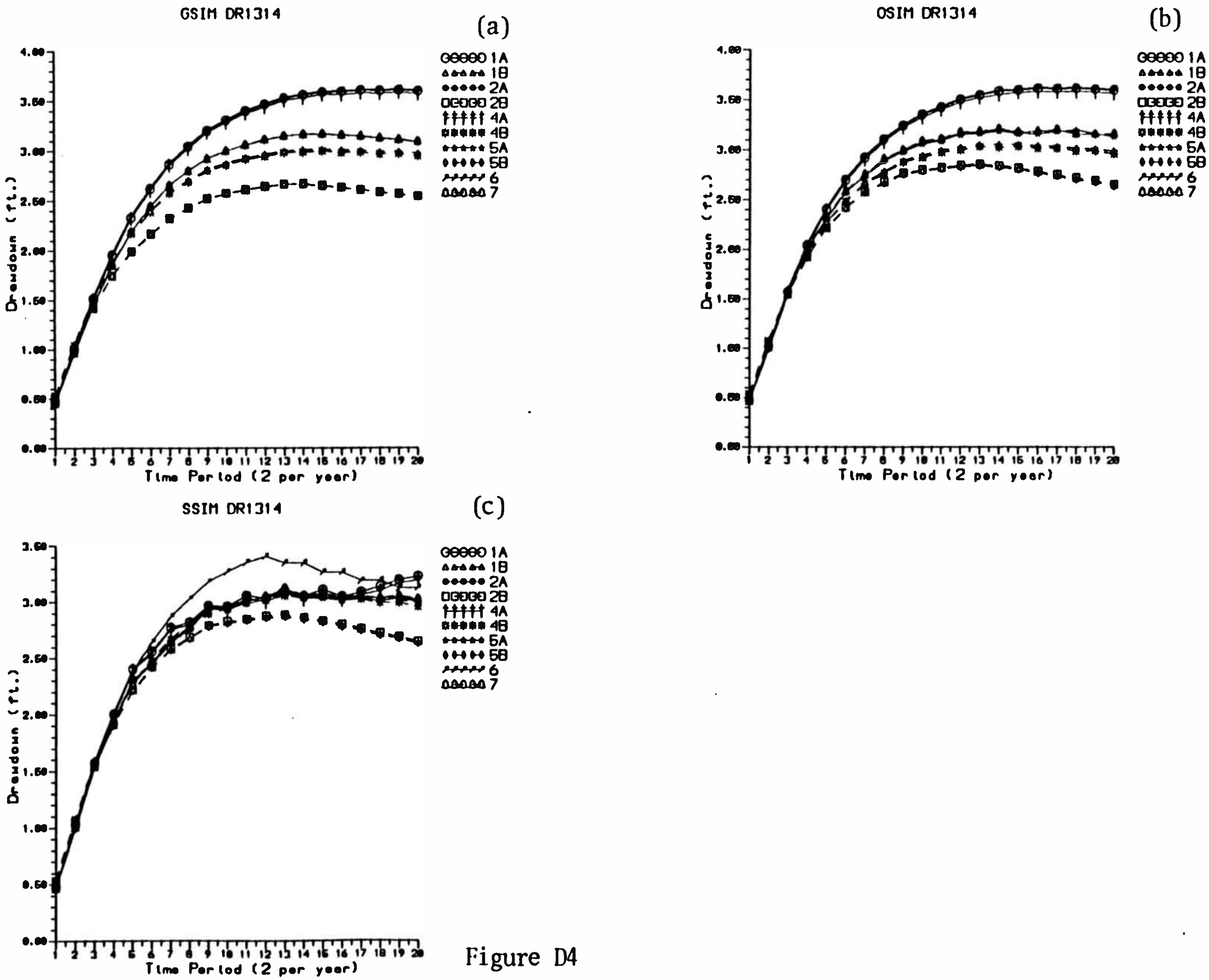

GSIM DR1314
(a)
OSIM DR1314
(b)
SSIM DR1314
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D4

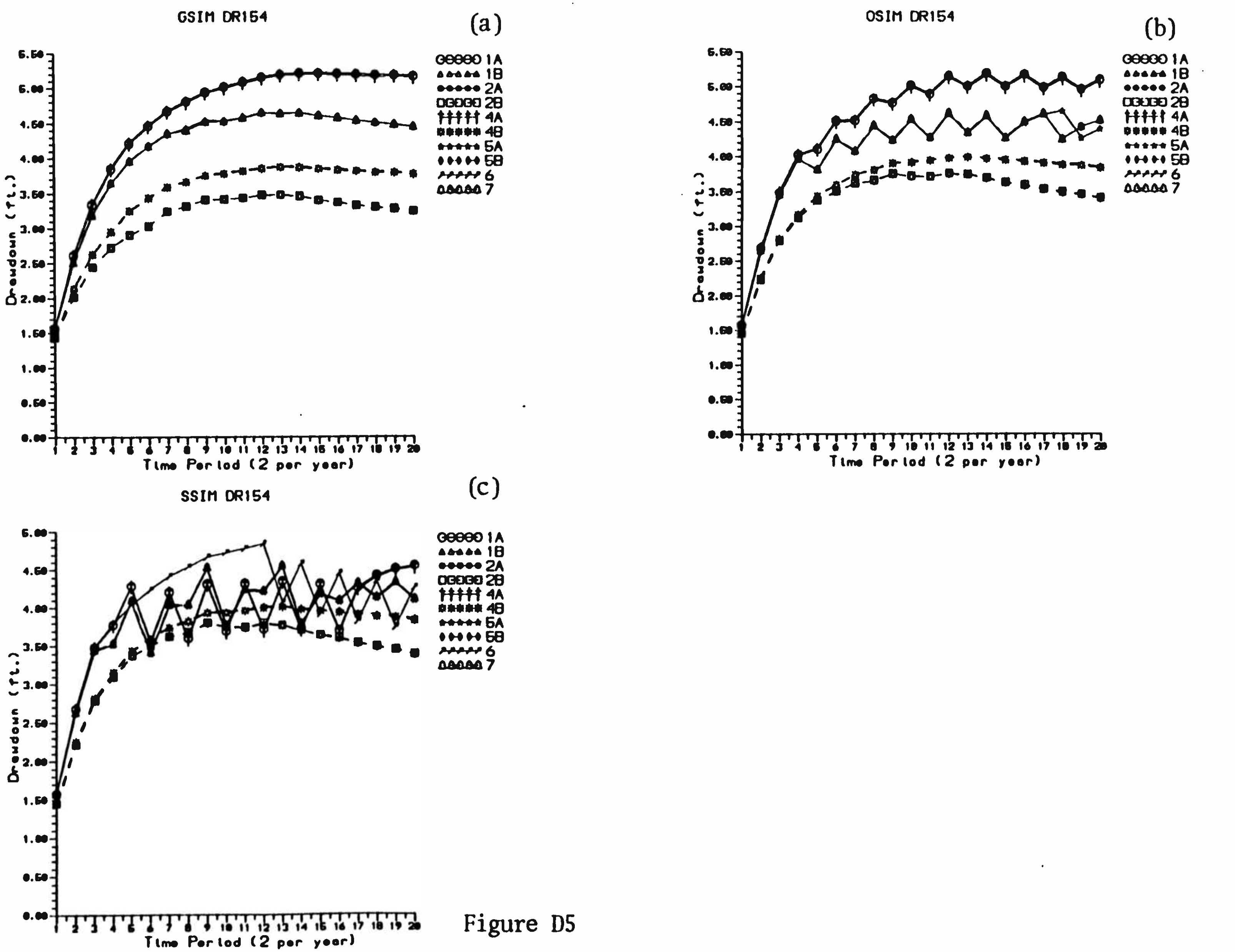
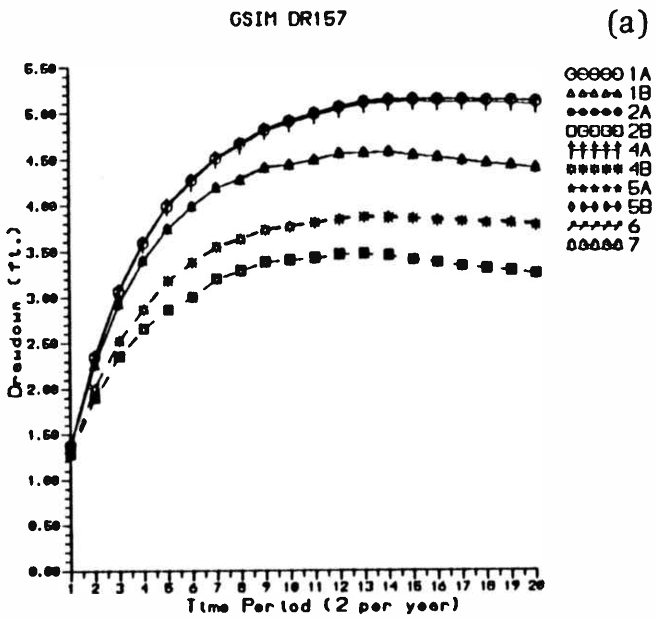
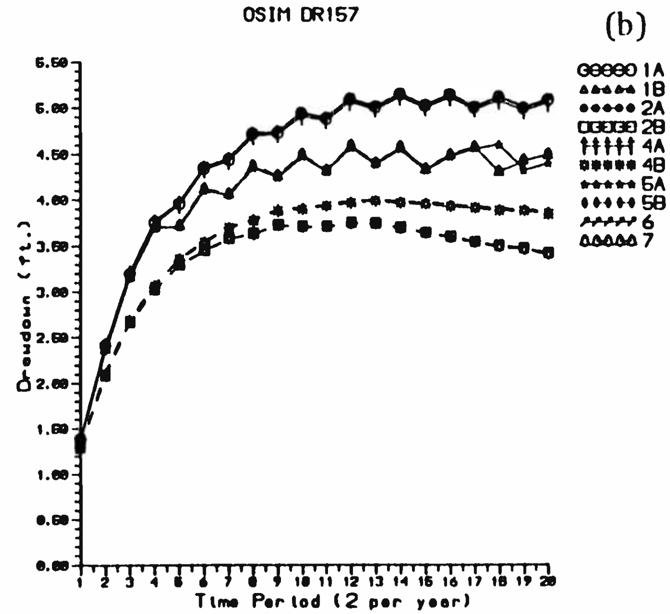

(a)
GSIM DR154
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7
(b)
OSIM DR154
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7
(c)
SSIM DR154
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D5


GSIM DR157
(a)
1A
1B
2A
2B
4A
4B
5A
5B
6
7
Drawdown (ft.)
Time Period (2 per year)


OSIM DR157
(b)
1A
1B
2A
2B
4A
4B
5A
5B
6
7
Drawdown (ft.)
Time Period (2 per year)

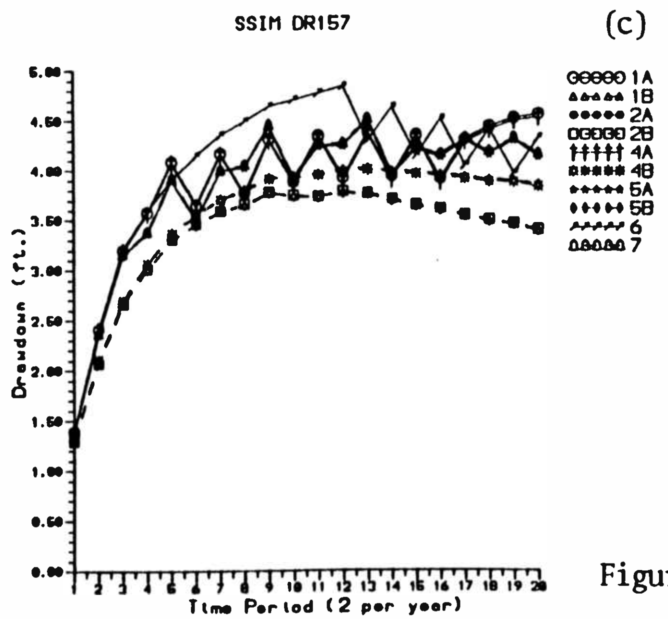

SSIM DR157
(c)
1A
1B
2A
2B
4A
4B
5A
5B
6
7
Drawdown (ft.)
Time Period (2 per year)

Figure D6

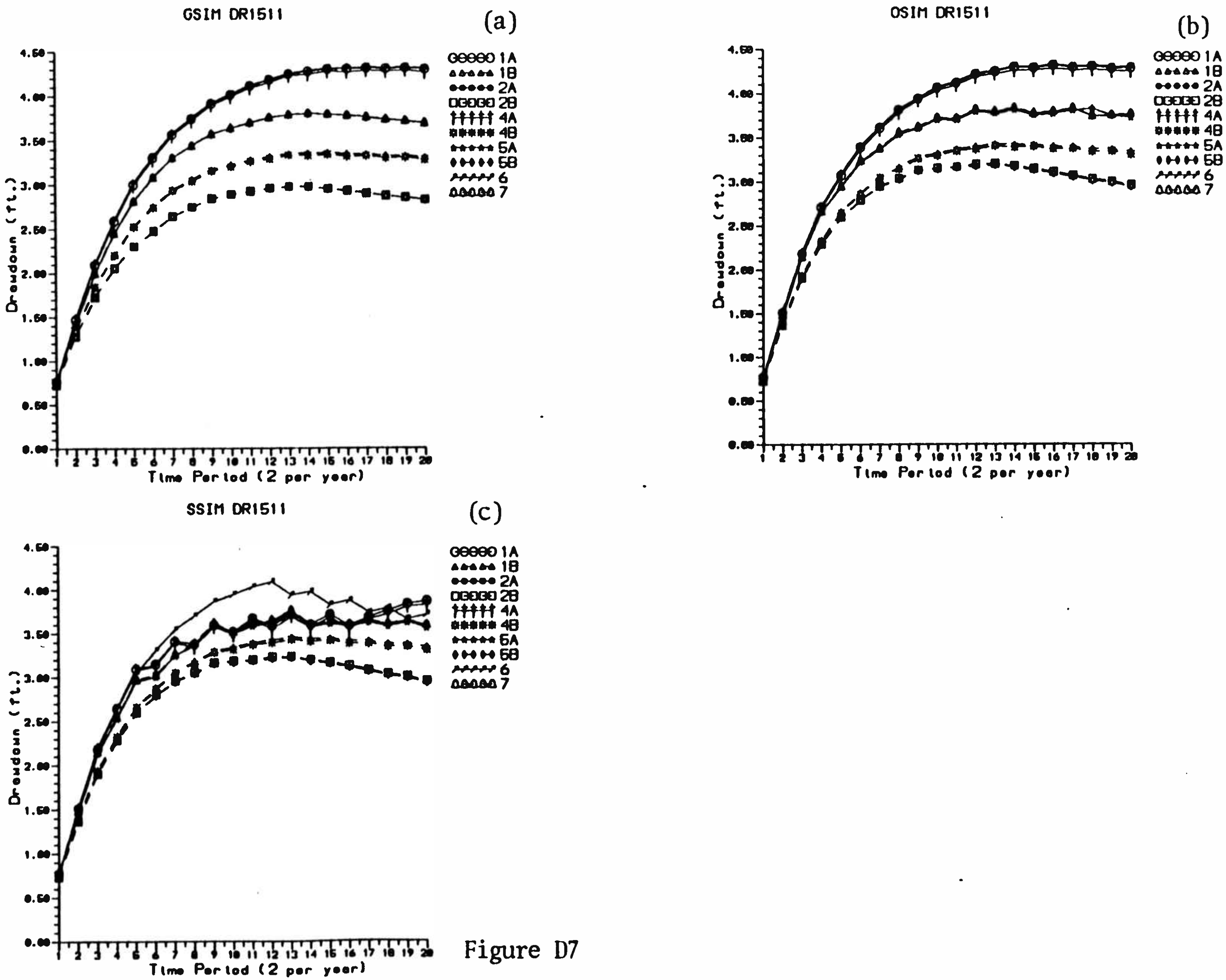
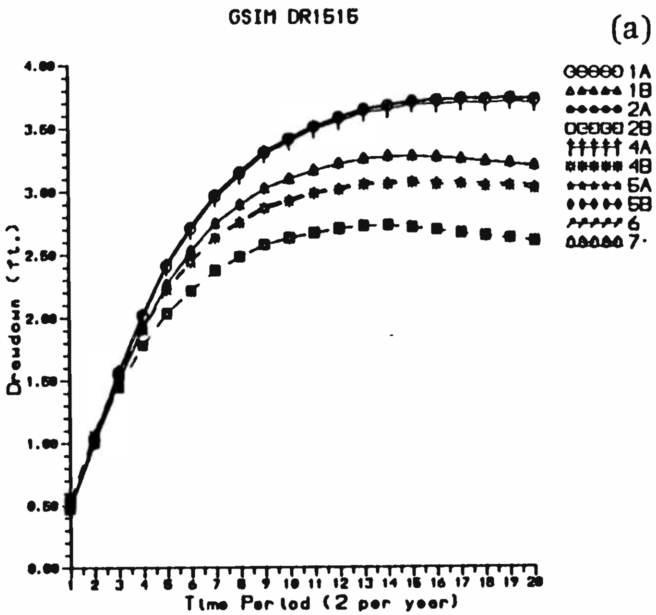
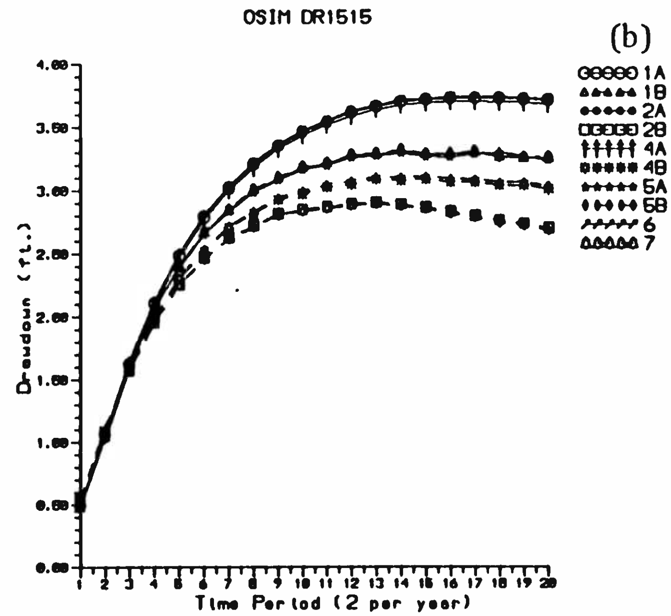

GSIM DR1511
(a)
OSIM DR1511
(b)
SSIM DR1511
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D7


GSIM DR1515
(a)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7


OSIM DR1515
(b)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

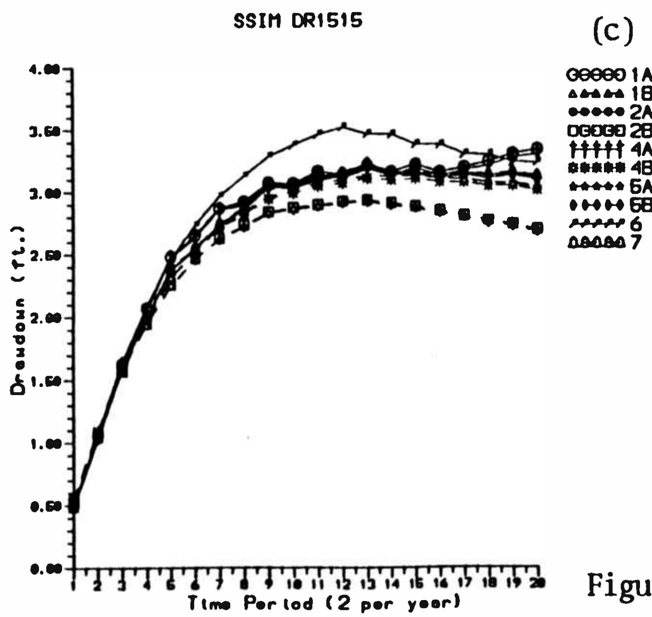
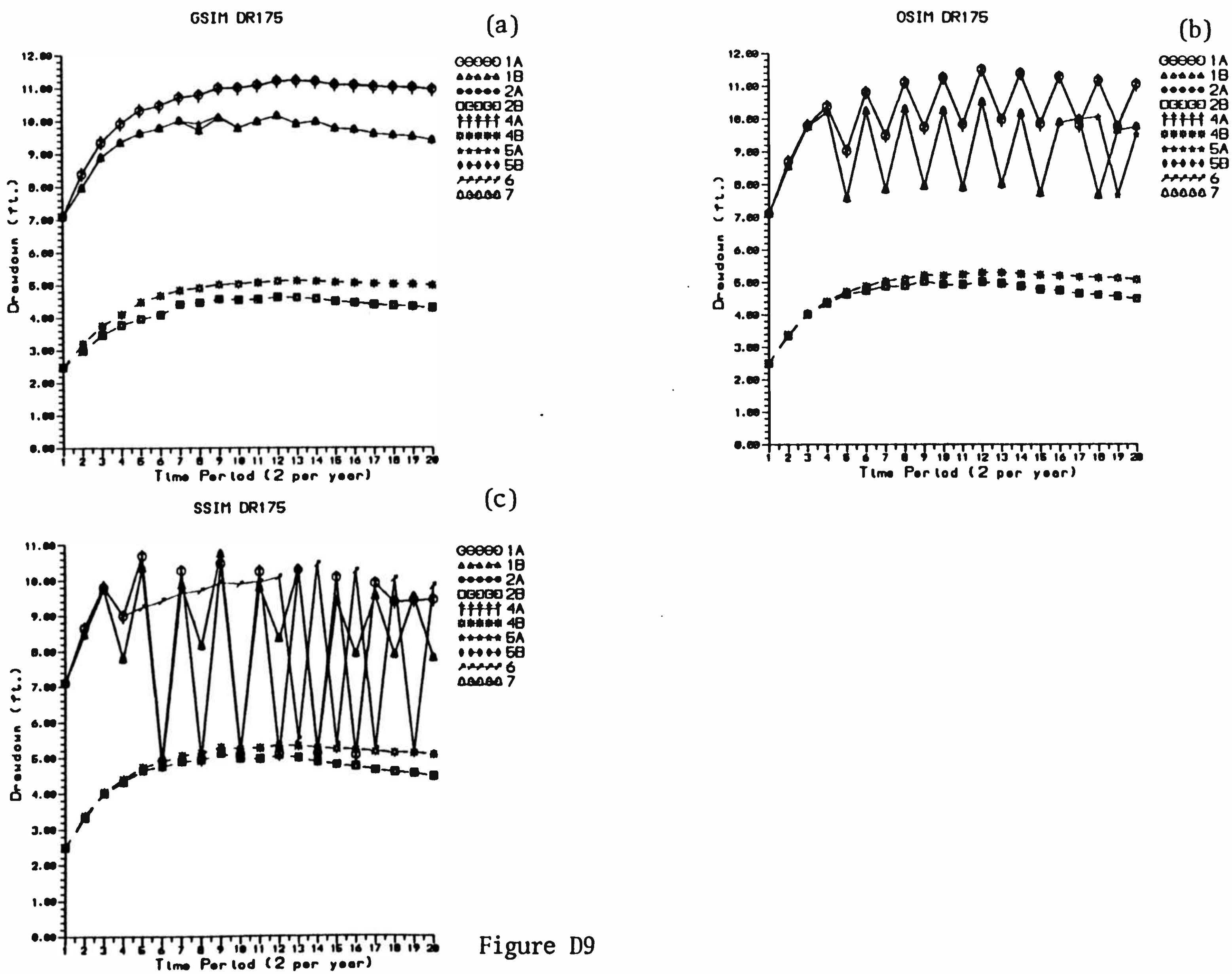

SSIM DR1515
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D8



GSIM DR175
(a)
OSIM DR175
(b)
SSIM DR175
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D9

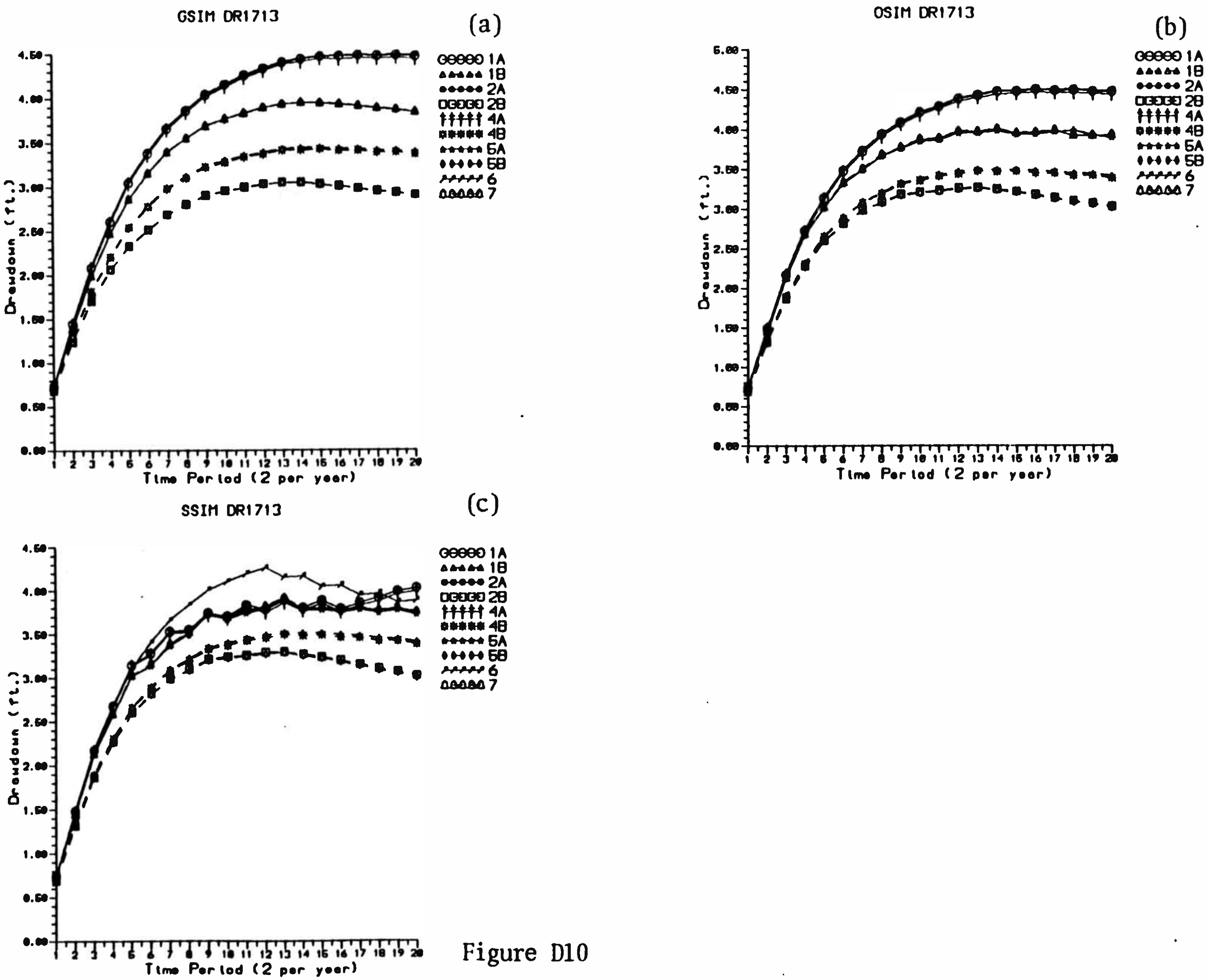
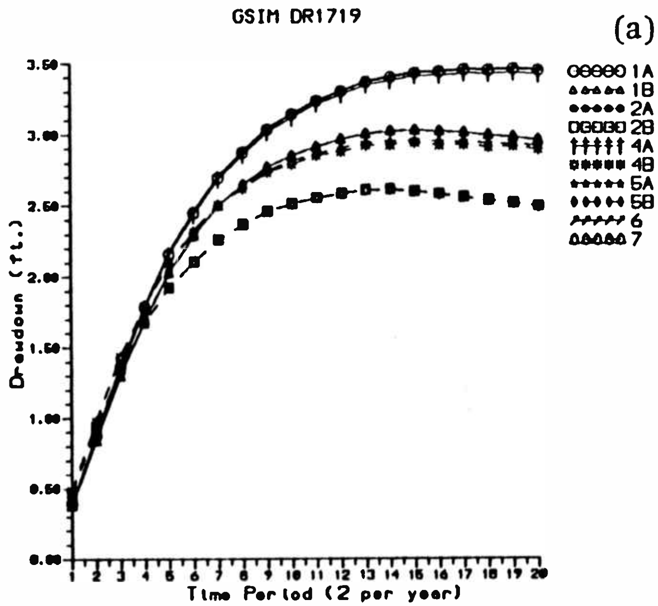
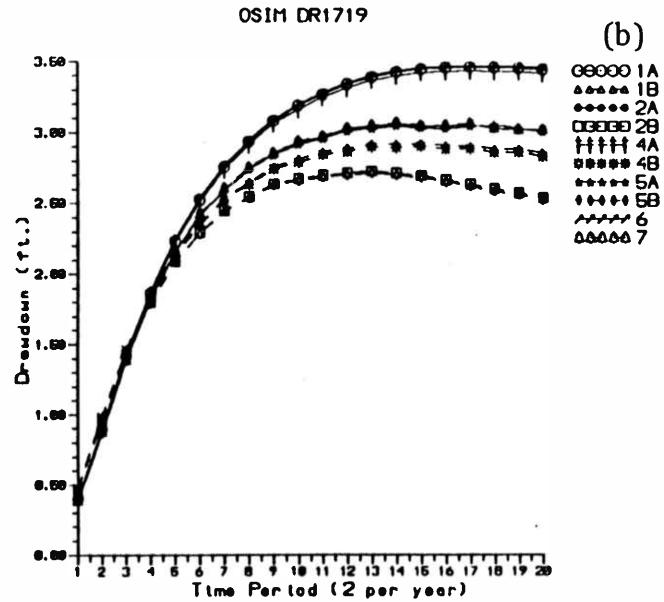

GSIM DR1713
(a)
OSIM DR1713
(b)
SSIM DR1713
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D10


GSIM DR1719
(a)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7


OSIM DR1719
(b)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

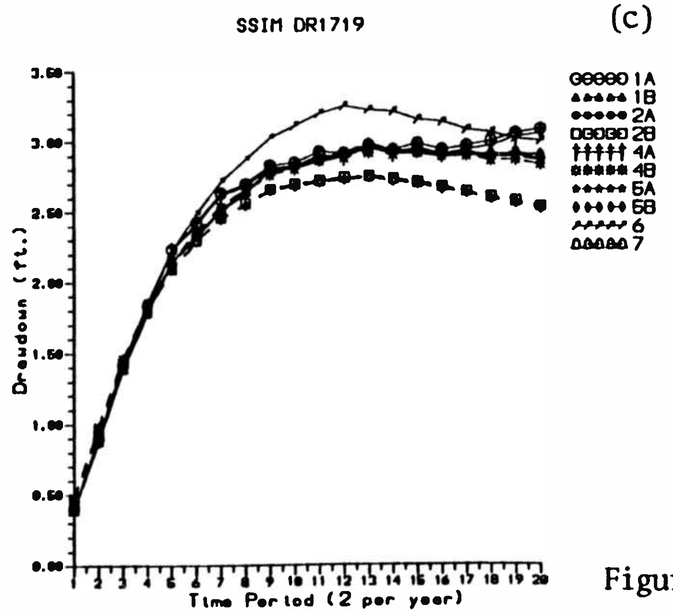

SSIM DR1719
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D11

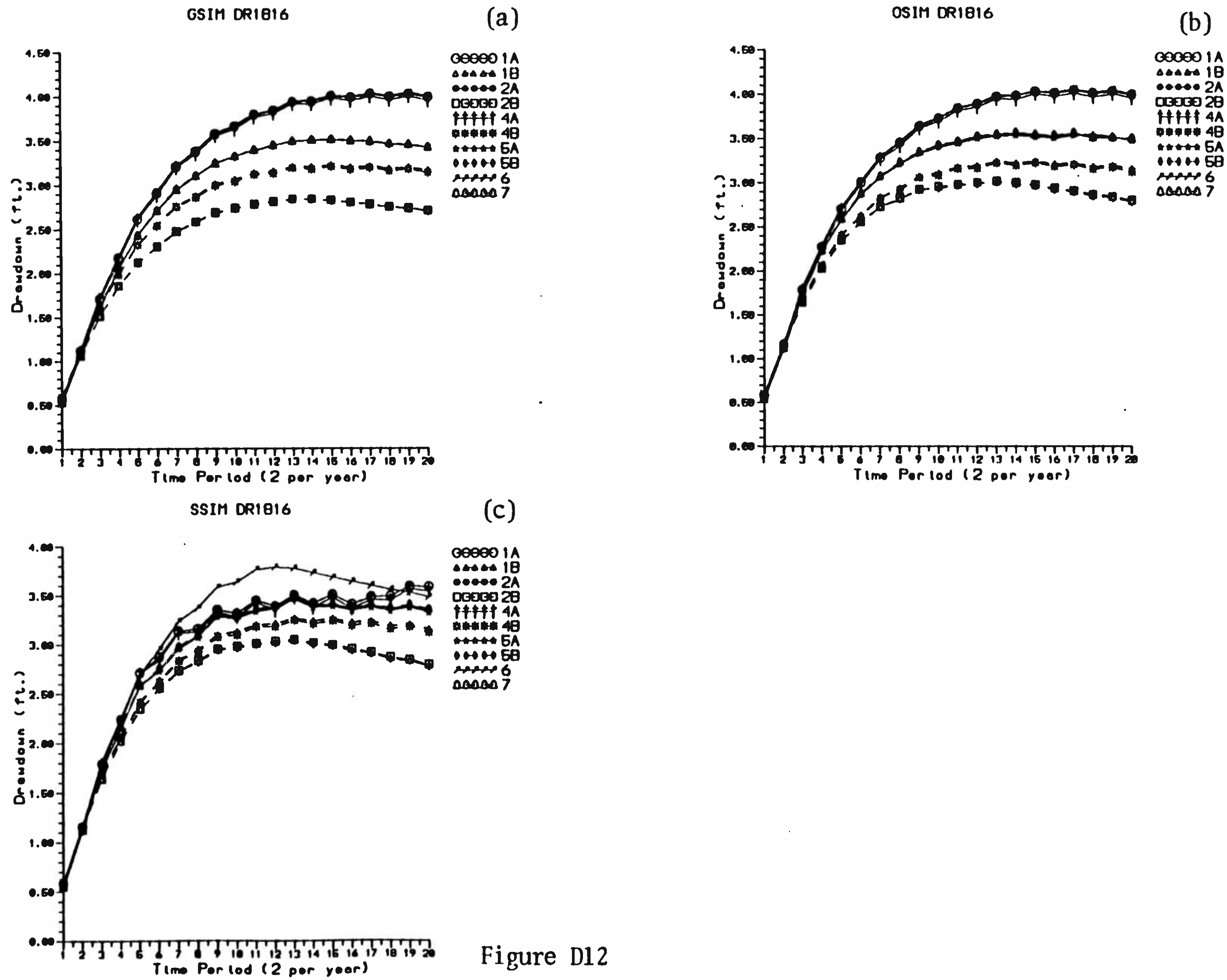

GSIM DR1816
(a)
OSIM DR1816
(b)
SSIM DR1816
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D12

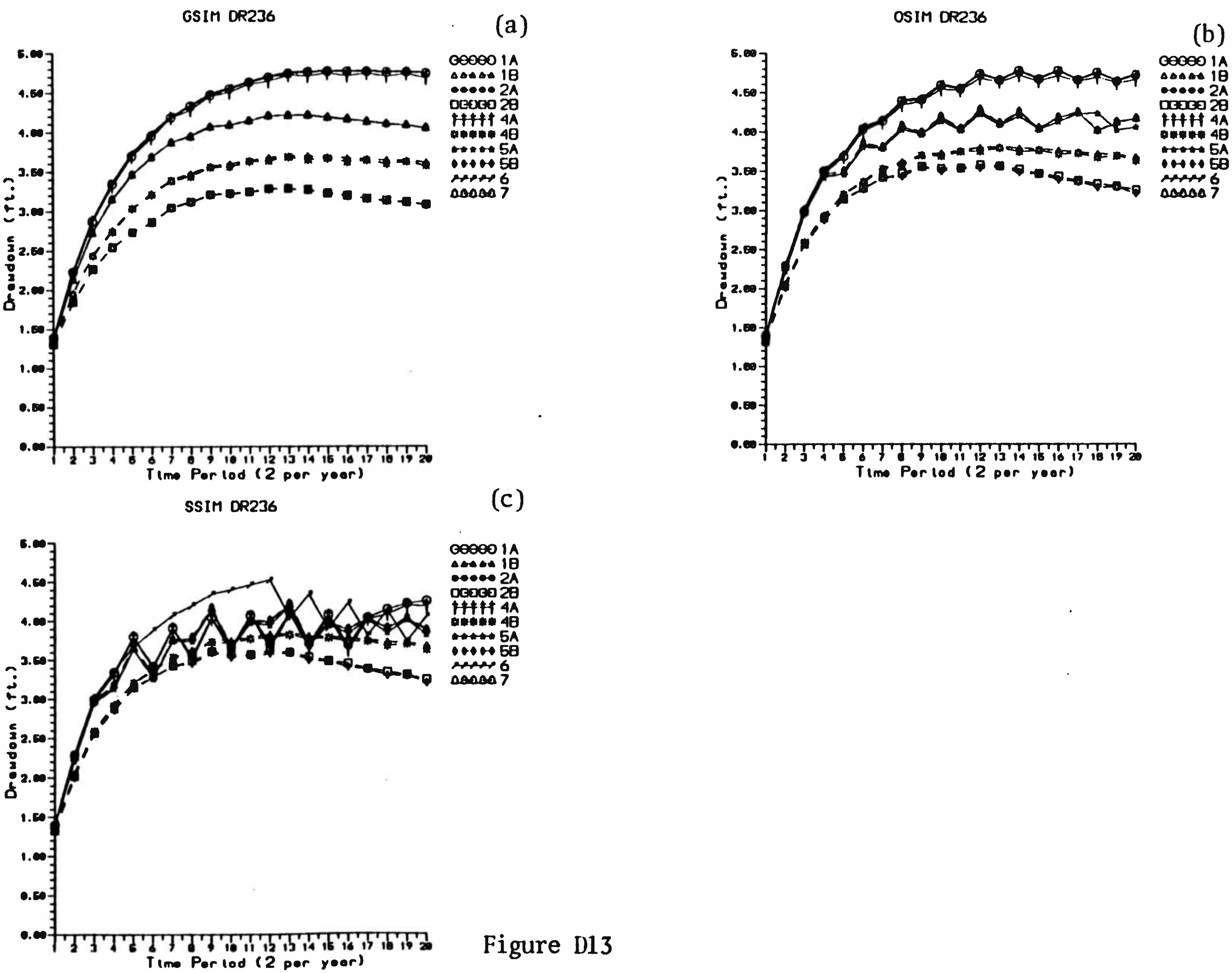
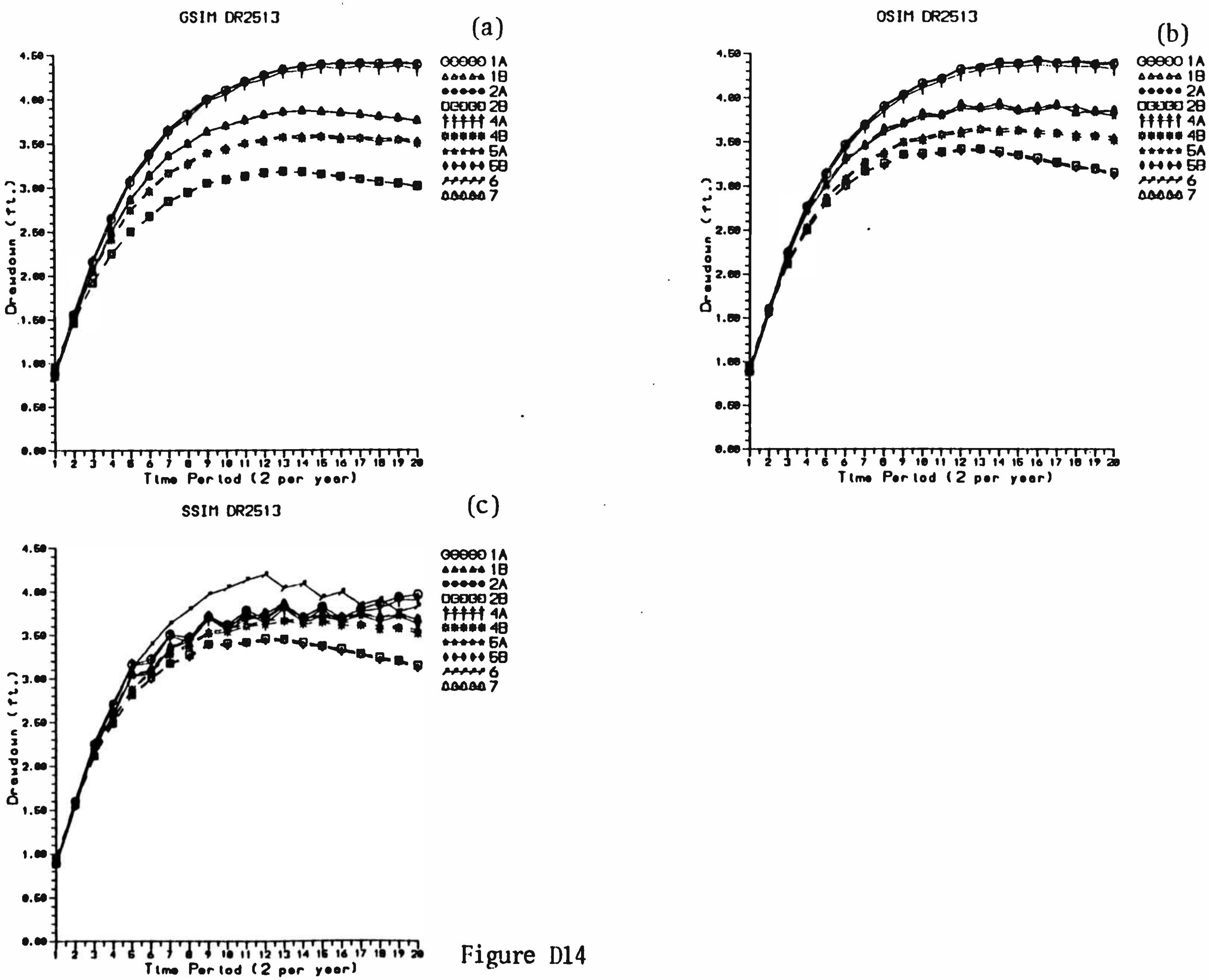
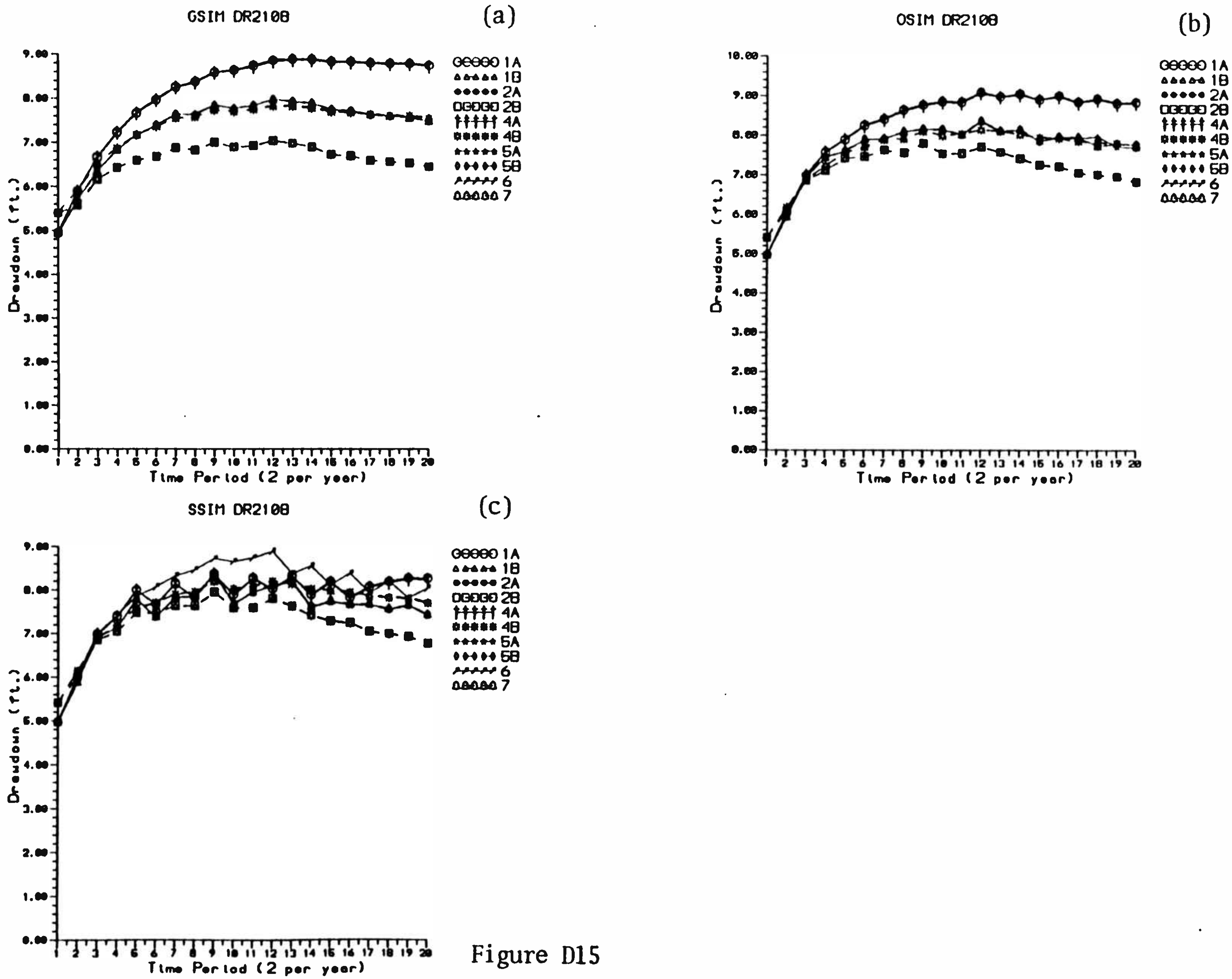

GSIM DR236
(a)
OSIM DR236
(b)
SSIM DR236
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D13



GSIM DR2513
(a)
OSIM DR2513
(b)
SSIM DR2513
(c)
Drawdown (ft.)
Time Period (2 per year)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D14

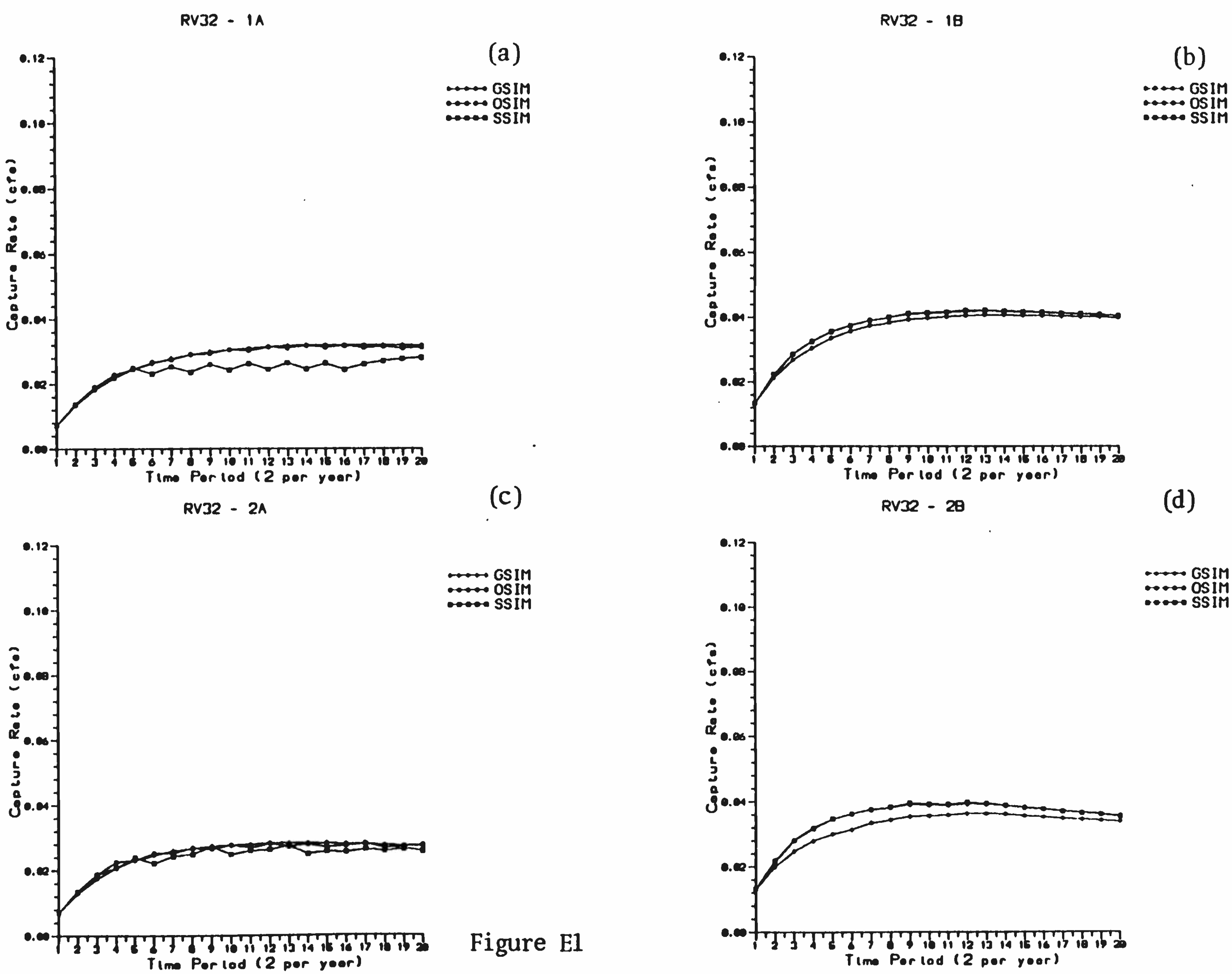


GSIM DR2108
(a)
OSIM DR2108
(b)
SSIM DR2108
(c)
Drawdown (ft.)
Time Period (2 per year)
1A
1B
2A
2B
4A
4B
5A
5B
6
7

Figure D15

APPENDIX E

River Capture Plots



RV32 - 1A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV32 - 1B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV32 - 2A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV32 - 2B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E1

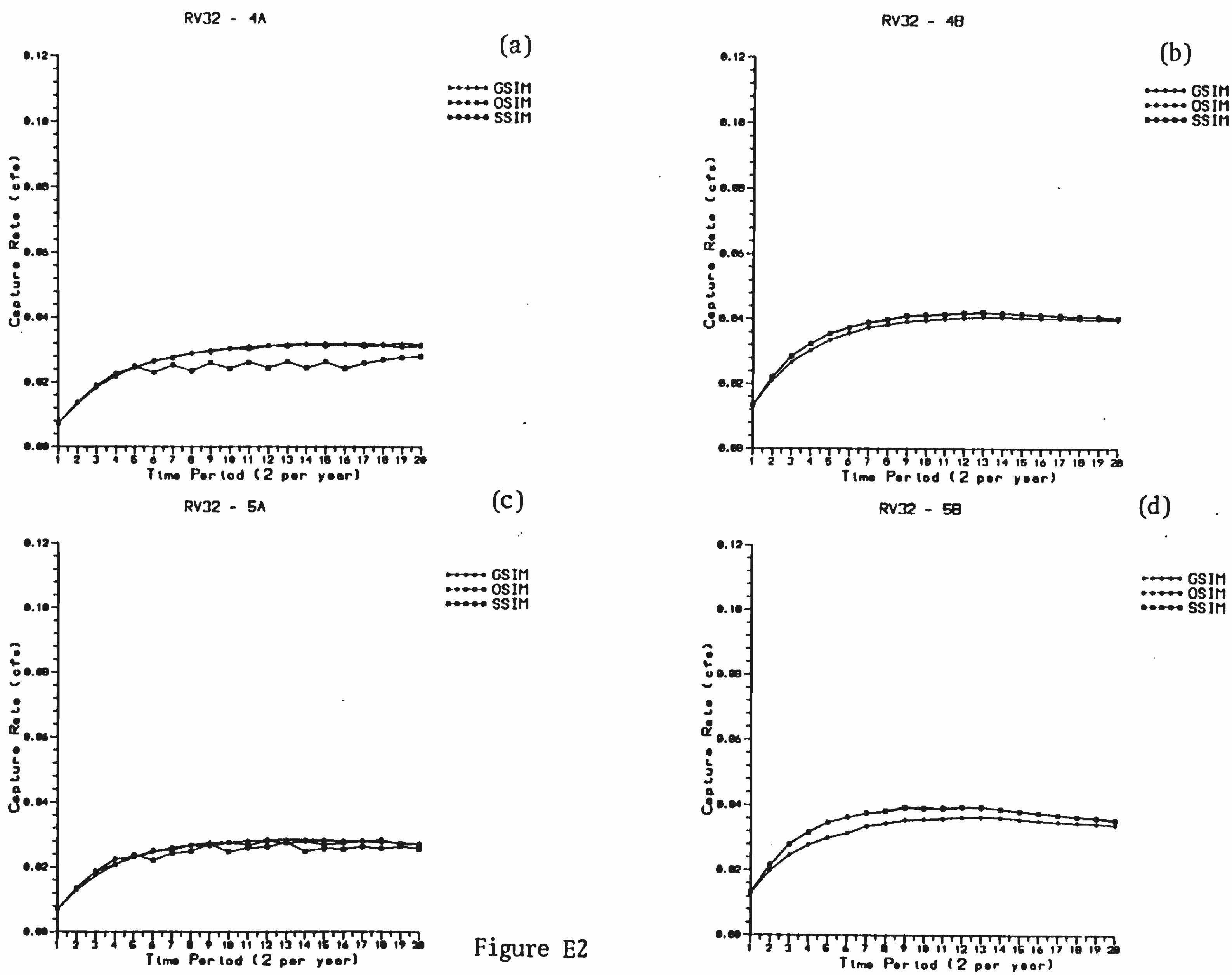

RV32 - 4A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV32 - 4B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV32 - 5A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV32 - 5B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E2

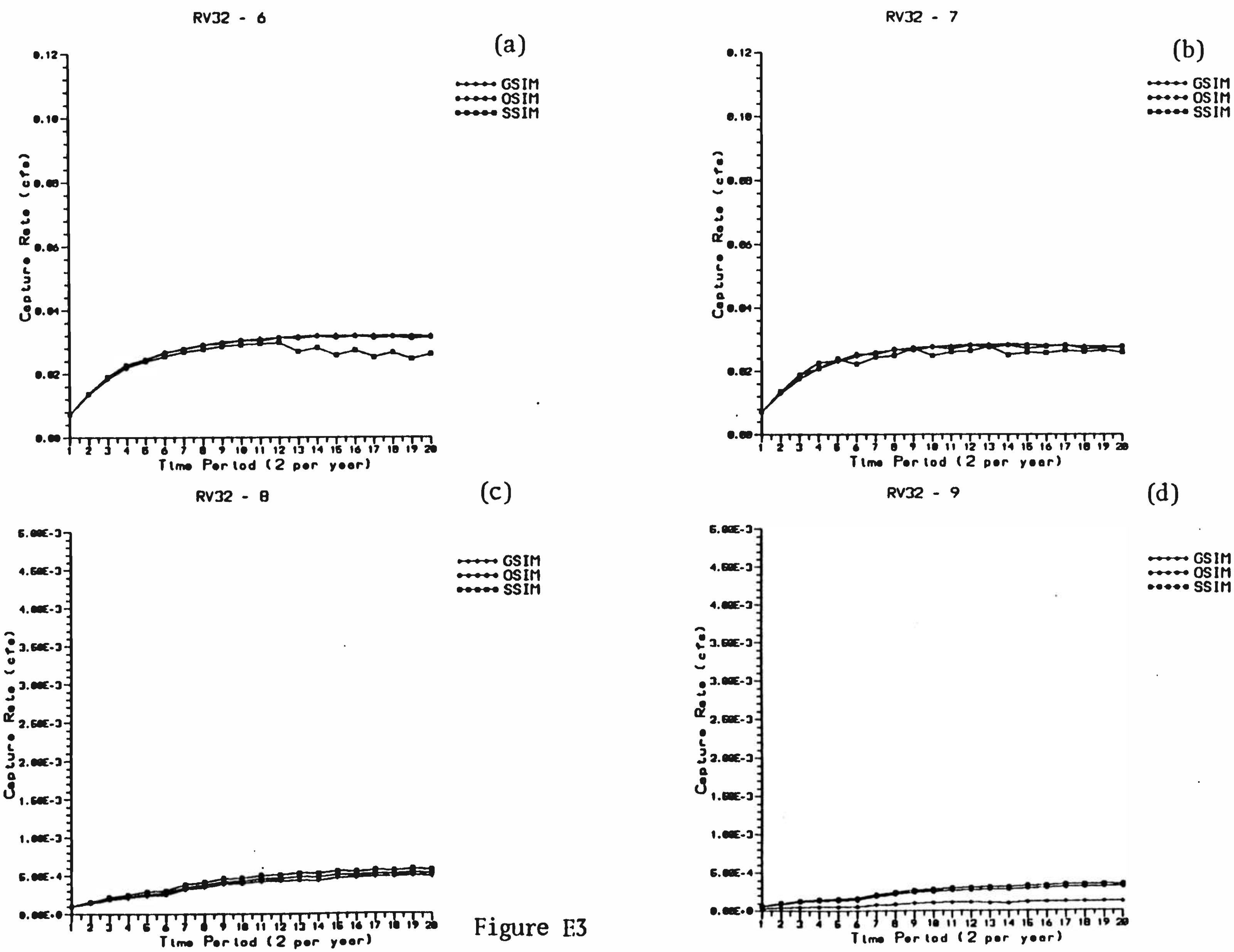

RV32 - 6
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV32 - 7
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV32 - 8
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV32 - 9
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E3

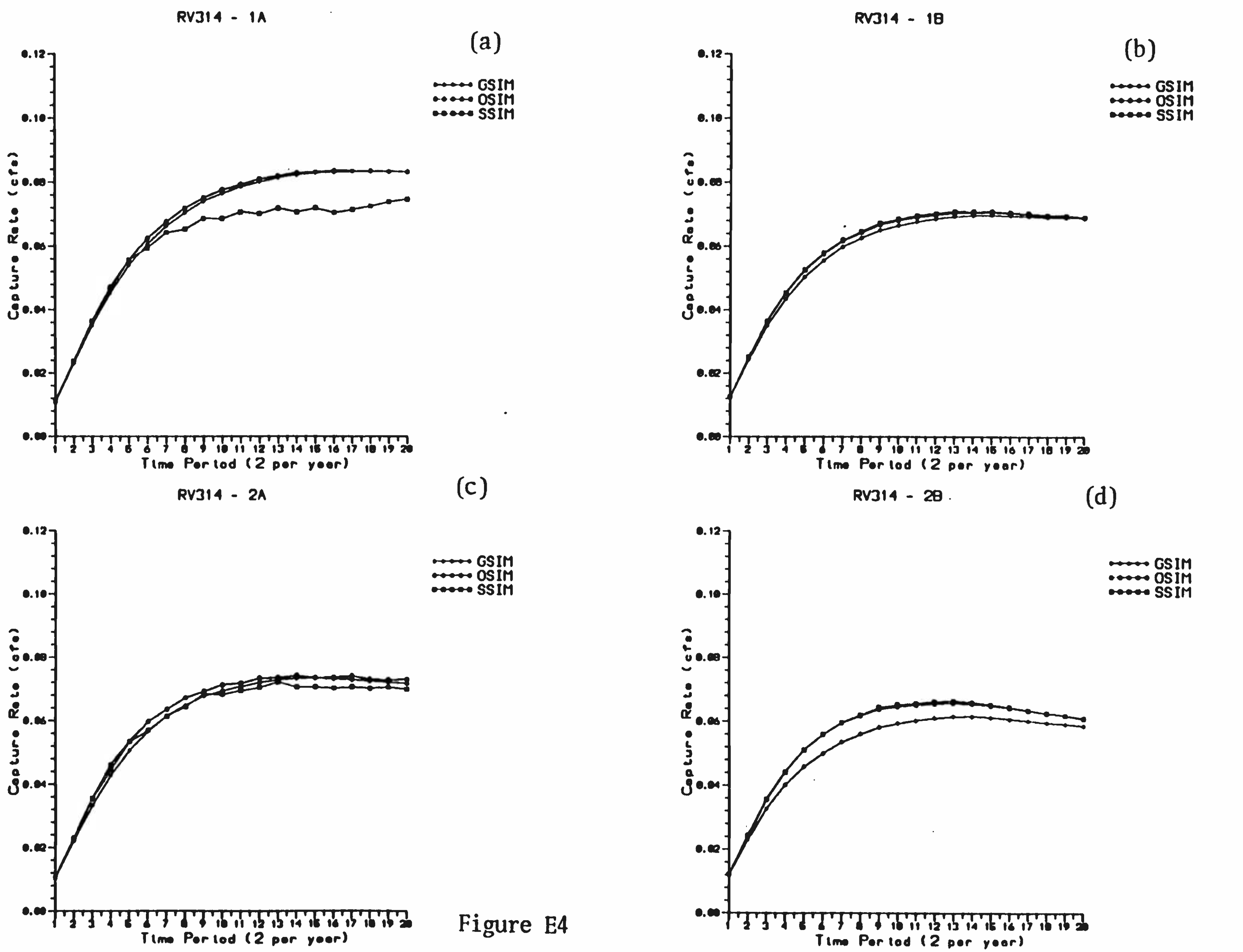
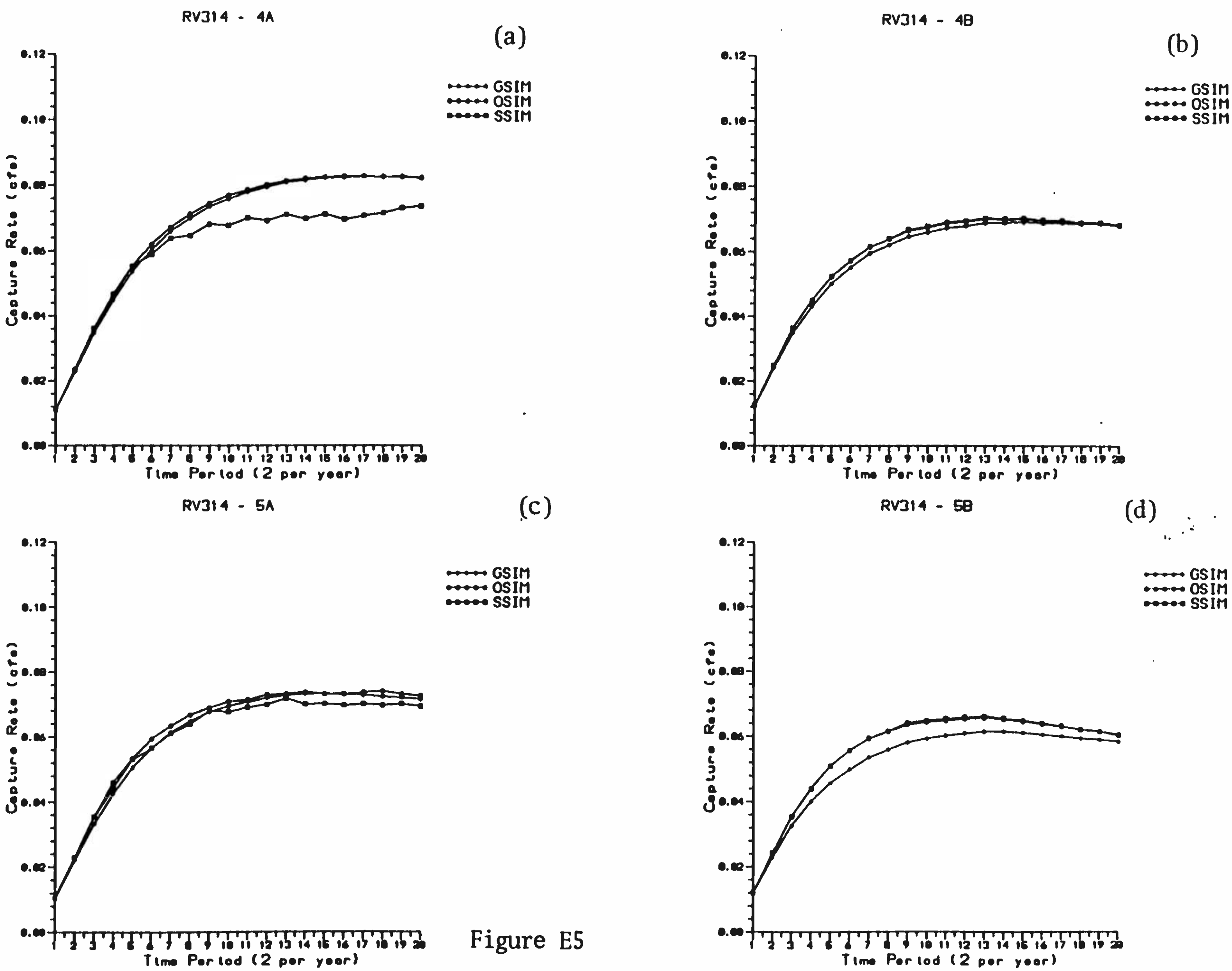

RV314 - 1A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV314 - 1B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV314 - 2A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV314 - 2B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E4



RV314 - 4A
(a)
RV314 - 4B
(b)
RV314 - 5A
(c)
RV314 - 5B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure E5

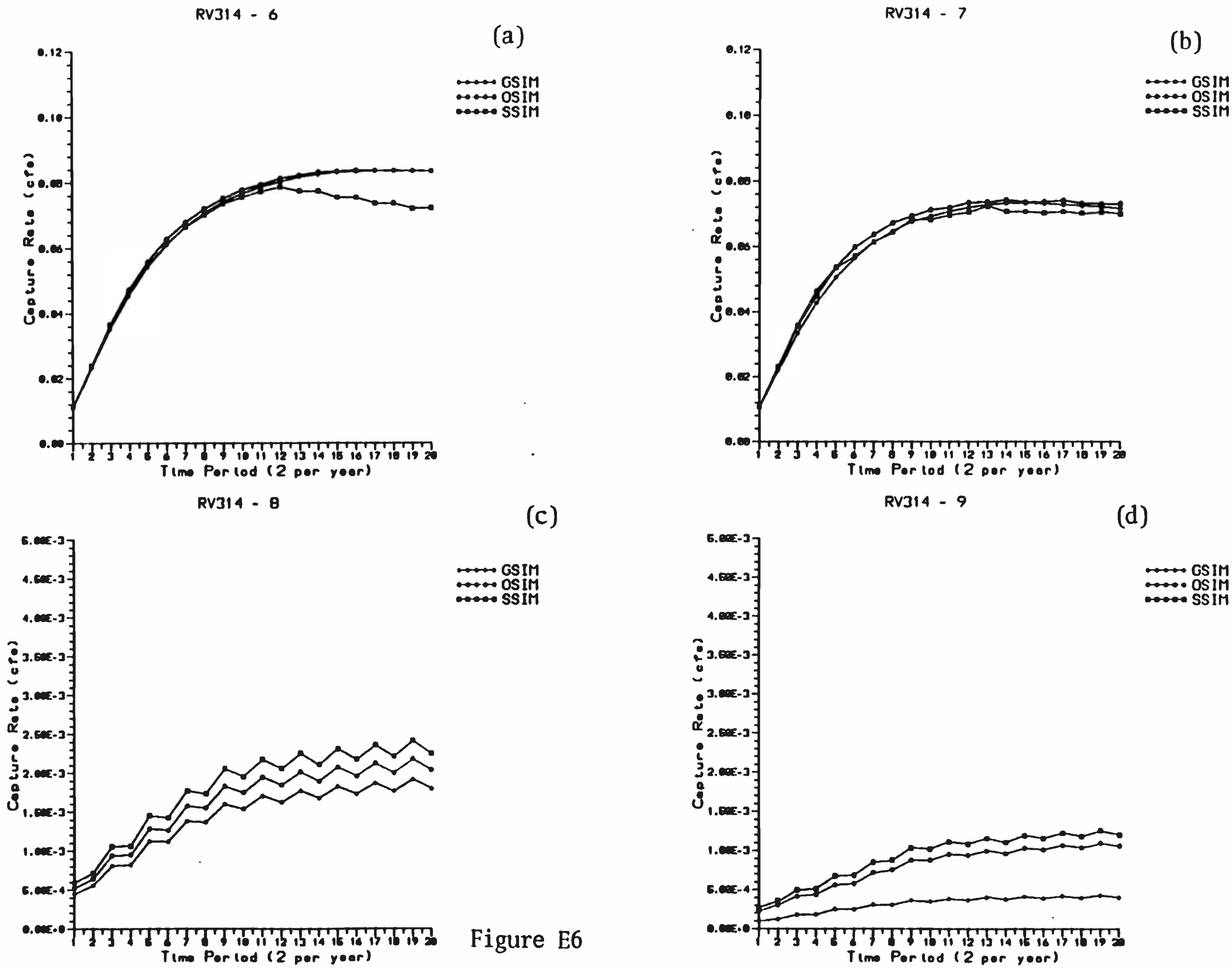

RV314 - 6
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV314 - 7
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV314 - 8
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV314 - 9
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E6

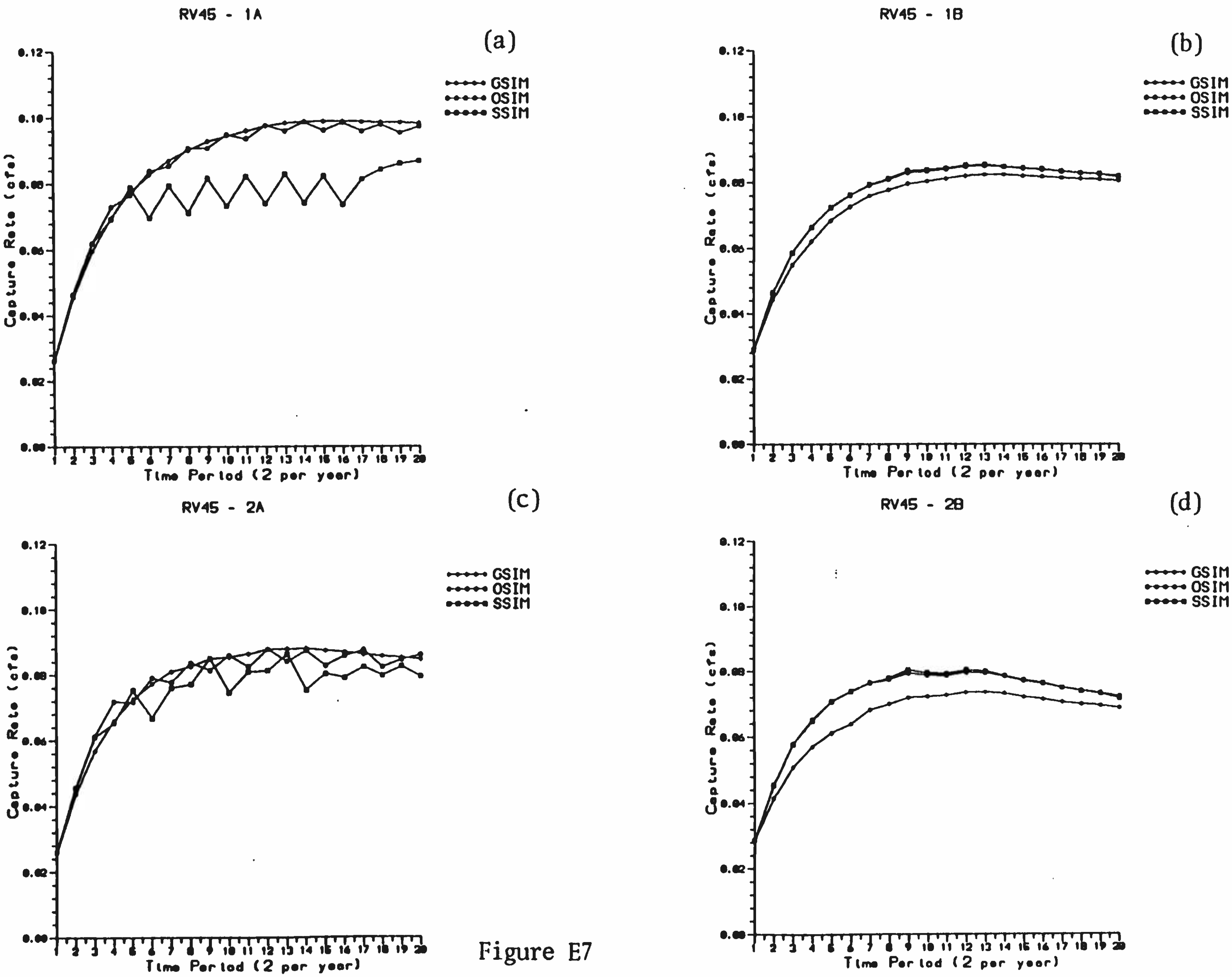

RV45 - 1A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV45 - 1B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV45 - 2A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV45 - 2B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E7

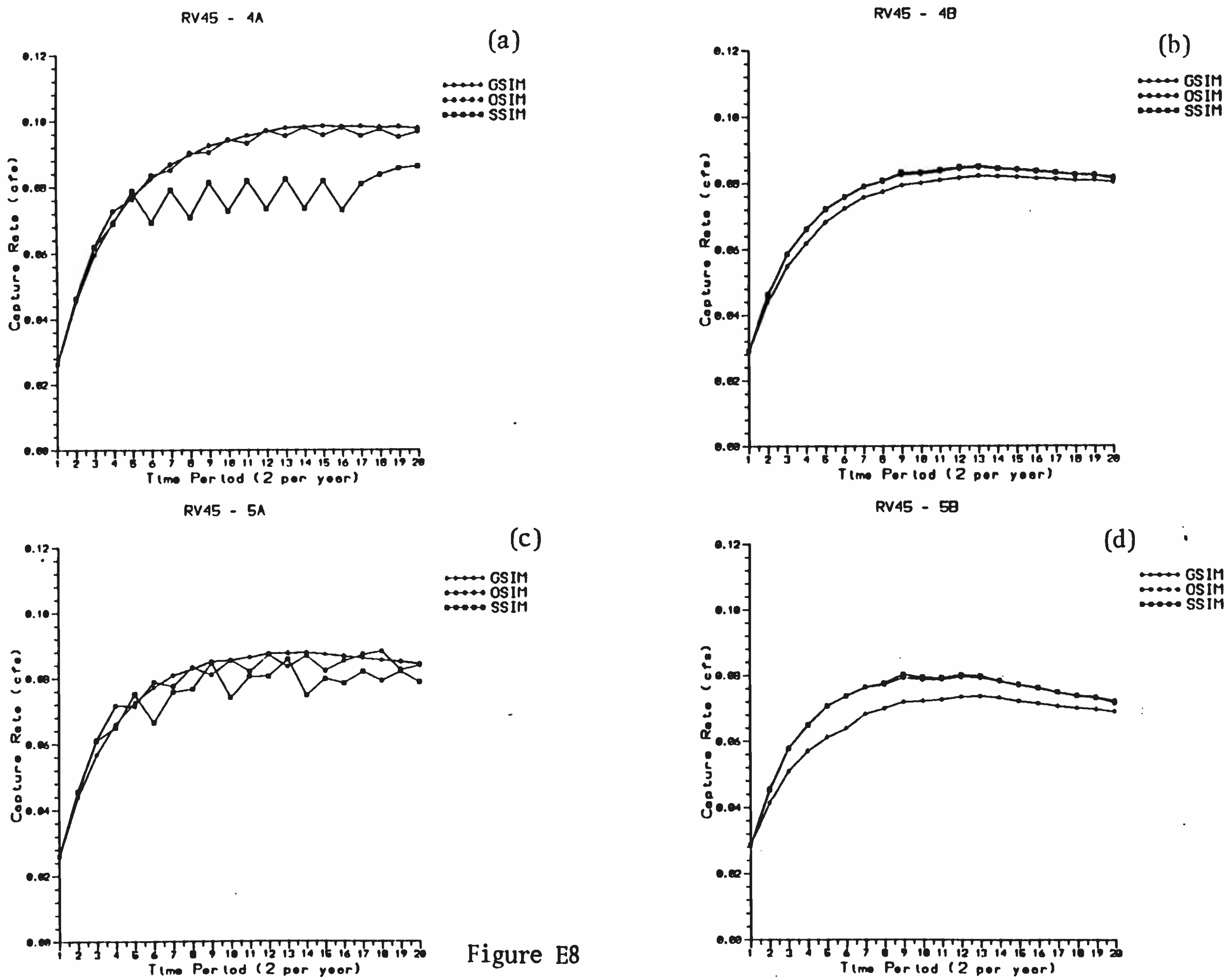

RV45 - 4A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV45 - 4B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV45 - 5A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV45 - 5B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E8

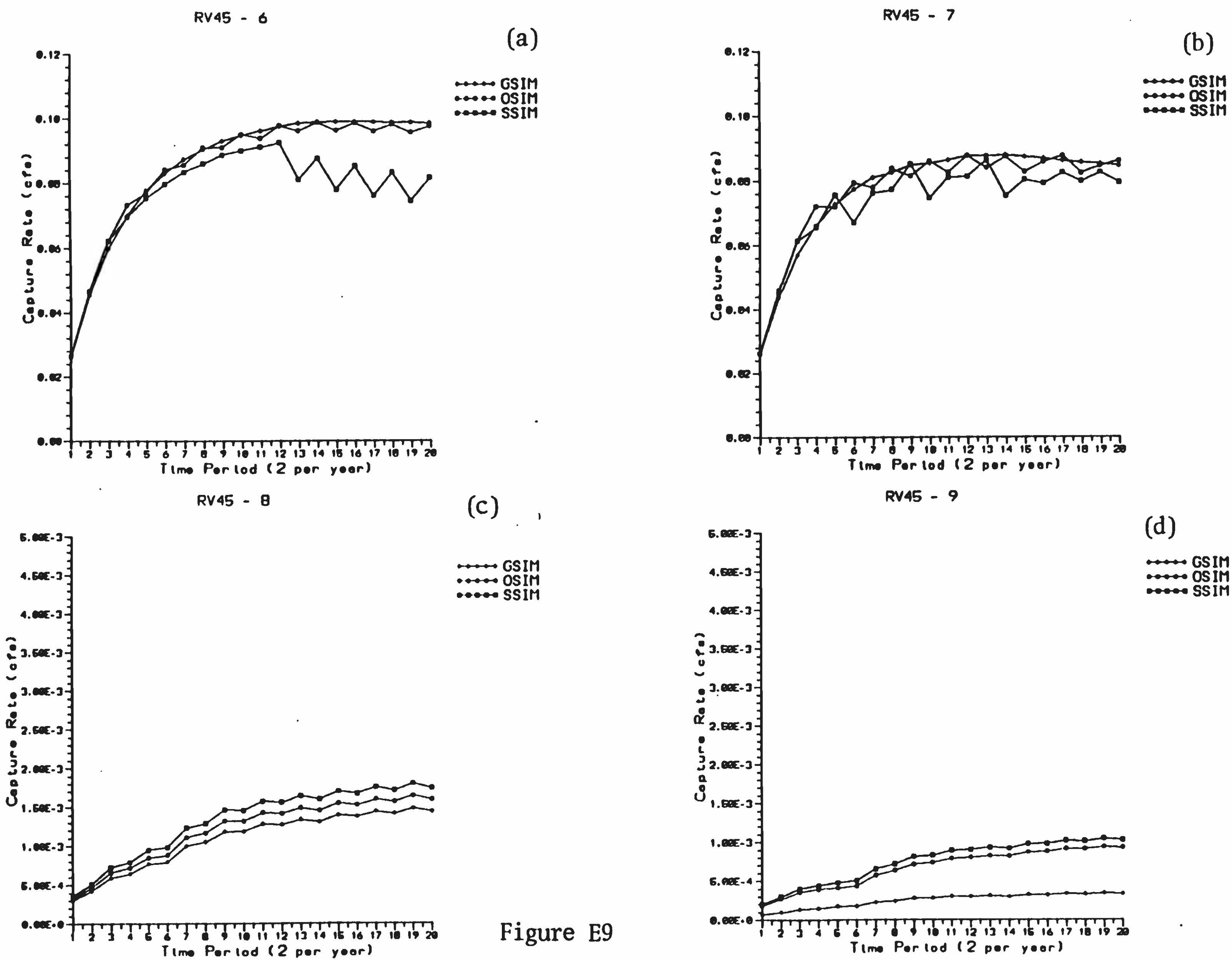

RV45 - 6
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV45 - 7
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV45 - 8
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV45 - 9
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E9

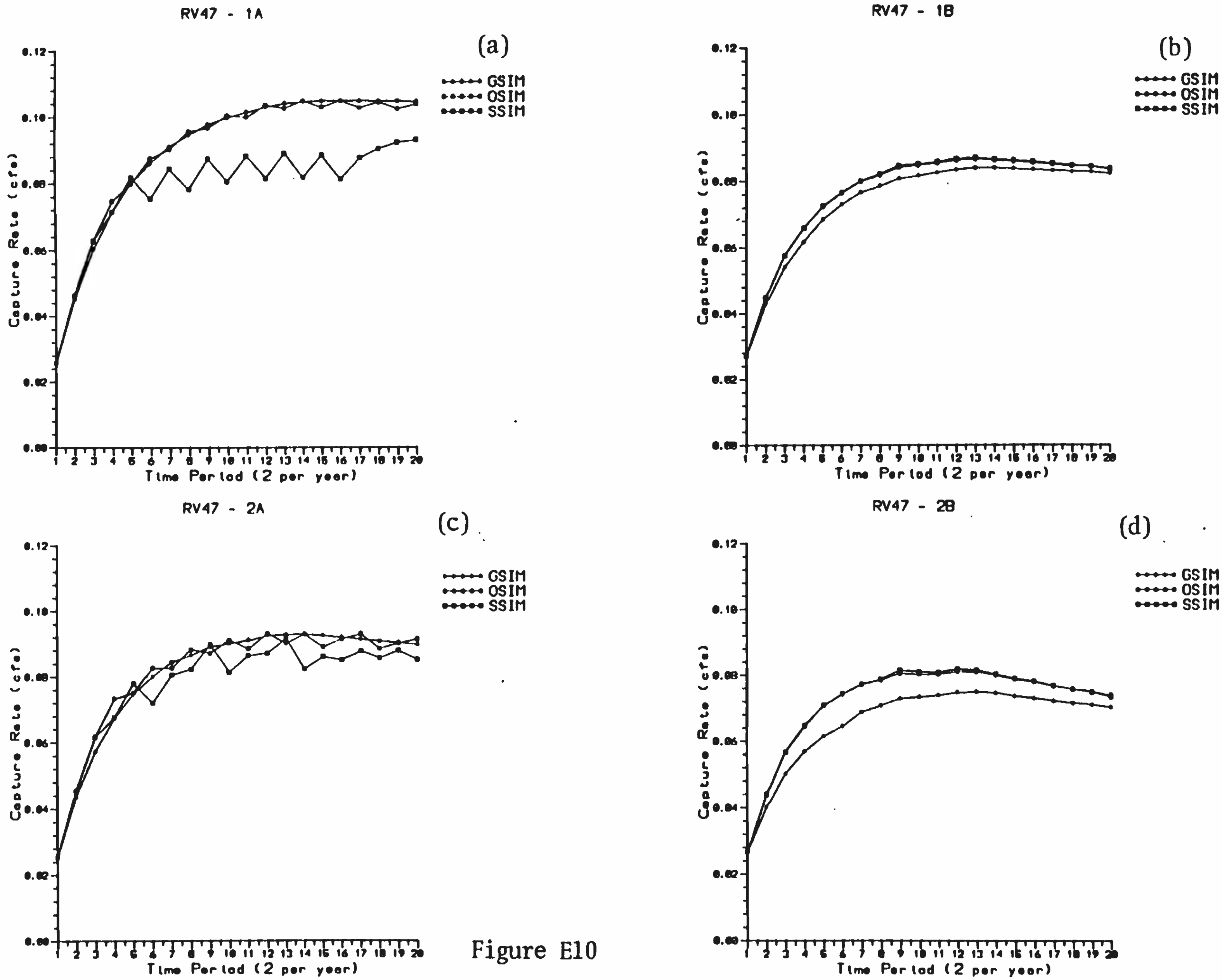

RV47 - 1A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV47 - 1B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV47 - 2A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV47 - 2B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E10

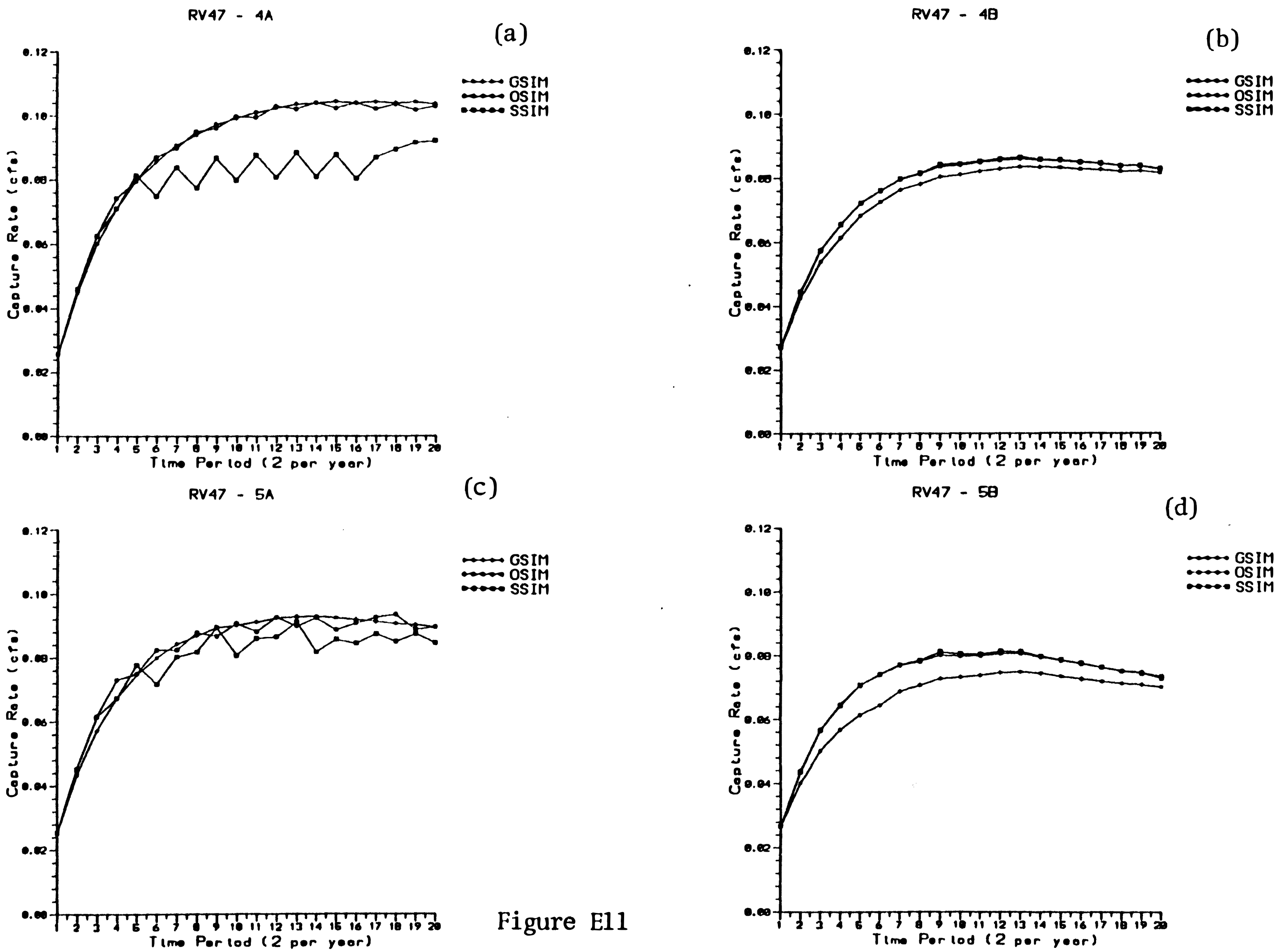

RV47 - 4A
(a)
RV47 - 4B
(b)
RV47 - 5A
(c)
RV47 - 5B
(d)
Capture Rate (cfs)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure E11

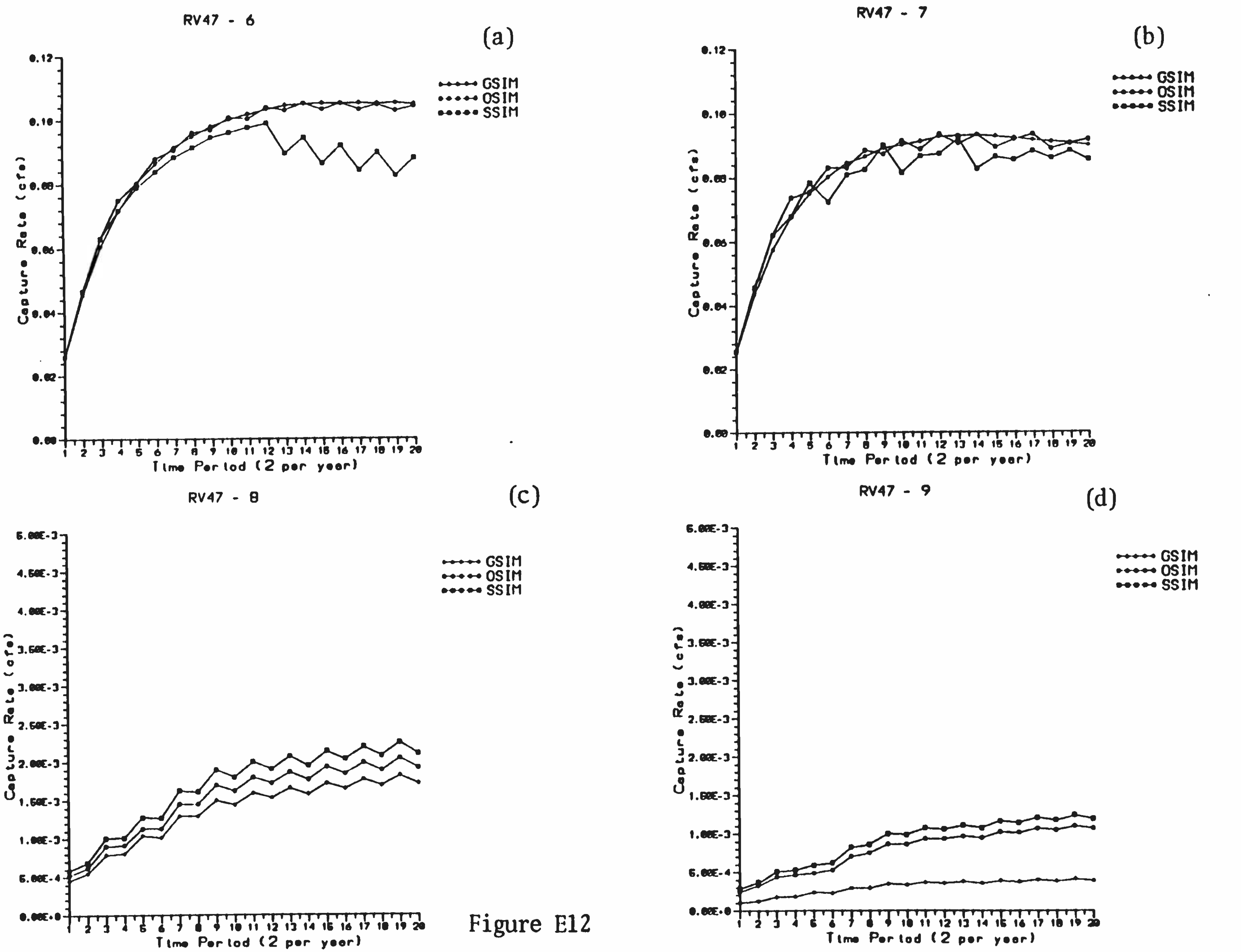

RV47 - 6
(a)
Capture Rate (cfs)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
RV47 - 7
(b)
Capture Rate (cfs)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
RV47 - 8
(c)
Capture Rate (cfs)
5.00E-3
4.50E-3
4.00E-3
3.50E-3
3.00E-3
2.50E-3
2.00E-3
1.50E-3
1.00E-3
5.00E-4
0.00E-0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM
RV47 - 9
(d)
Capture Rate (cfs)
5.00E-3
4.50E-3
4.00E-3
3.50E-3
3.00E-3
2.50E-3
2.00E-3
1.50E-3
1.00E-3
5.00E-4
0.00E-0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure E12

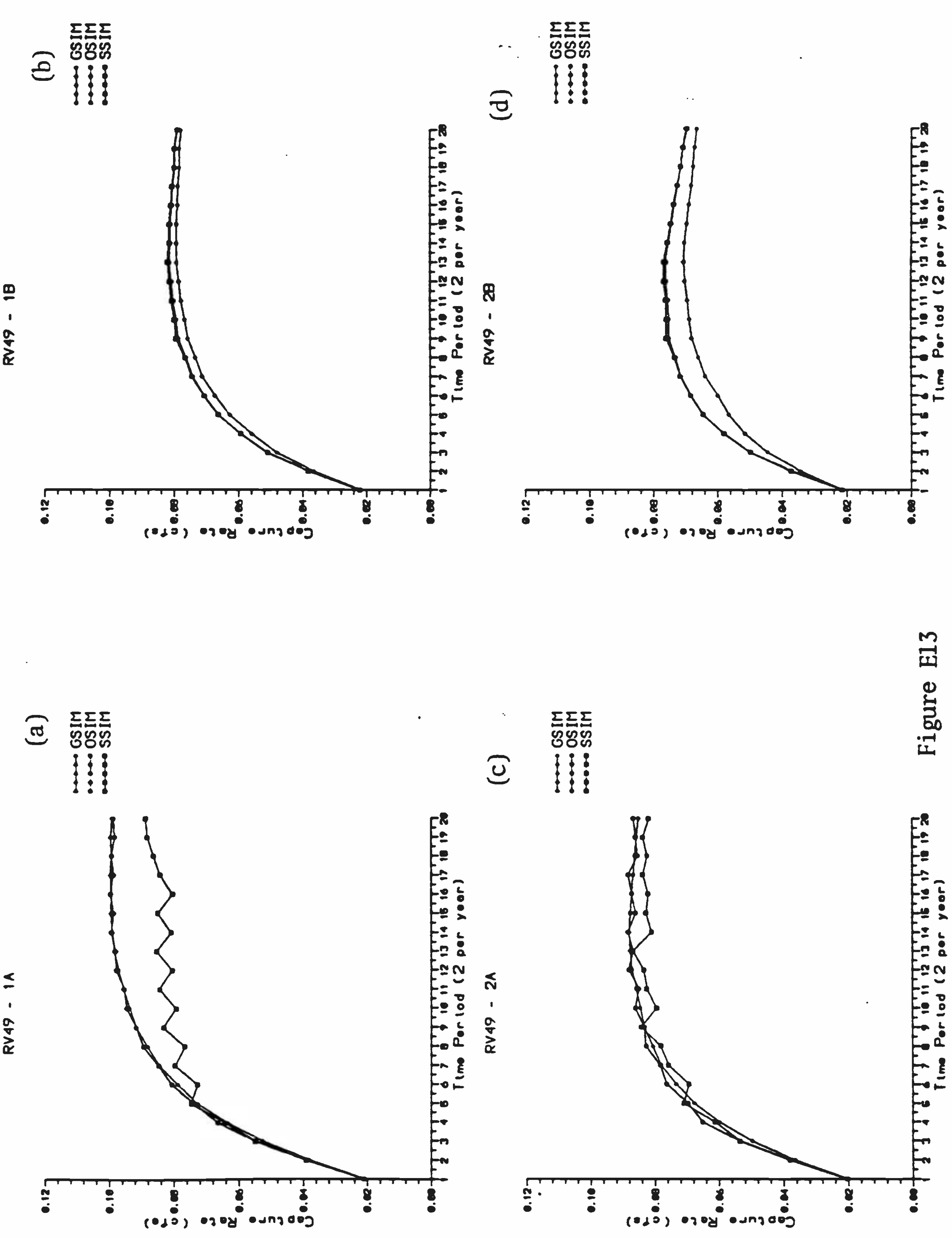

(a)
RV49 - 1A
(b)
RV49 - 1B
(c)
RV49 - 2A
(d)
RV49 - 2B
GSIM
OSIM
SSIM
Capture Rate (cfe)
Time Period (2 per year)
0.00
0.02
0.04
0.06
0.08
0.10
0.12

Figure E13

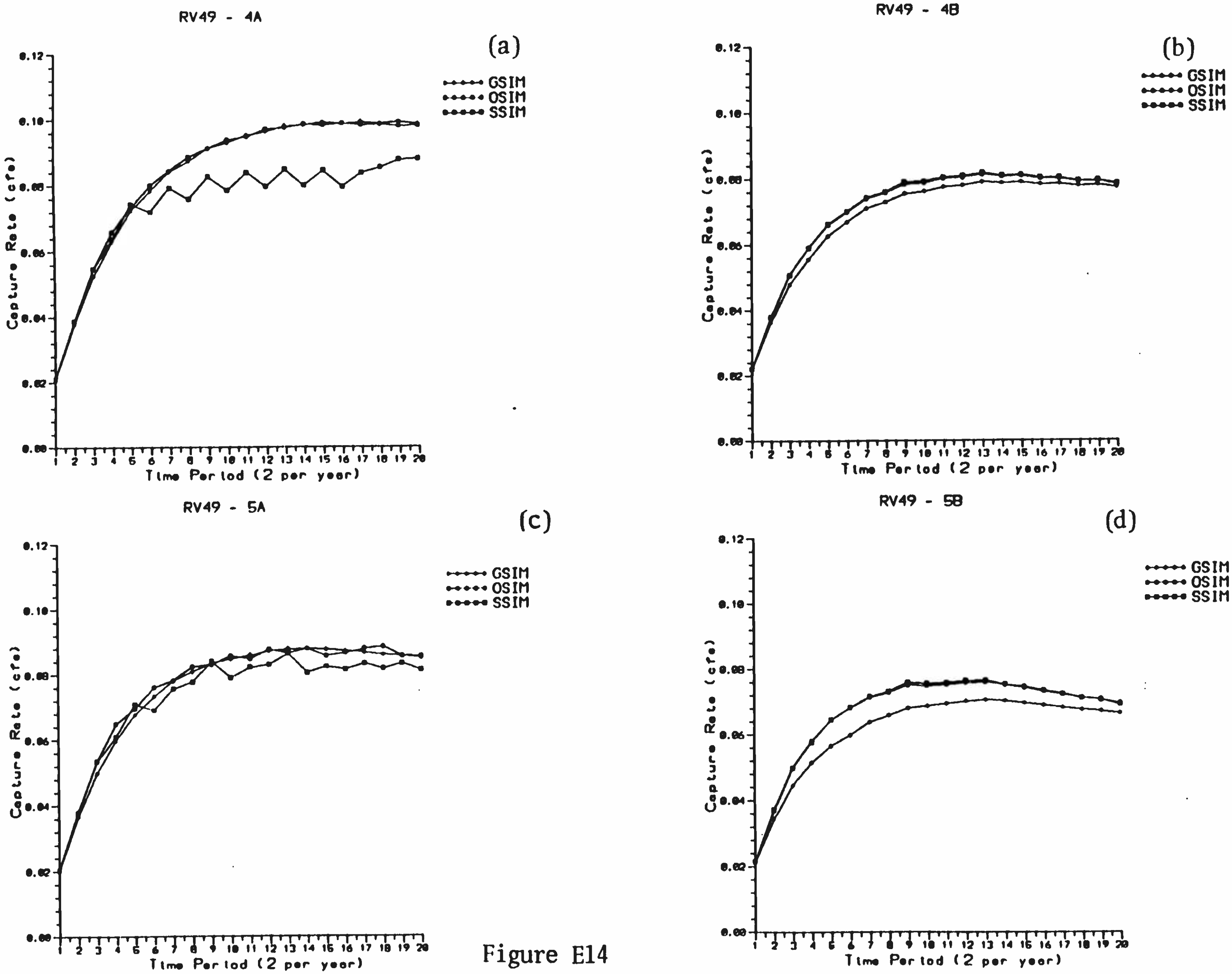

RV49 - 4A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV49 - 4B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV49 - 5A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV49 - 5B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E14

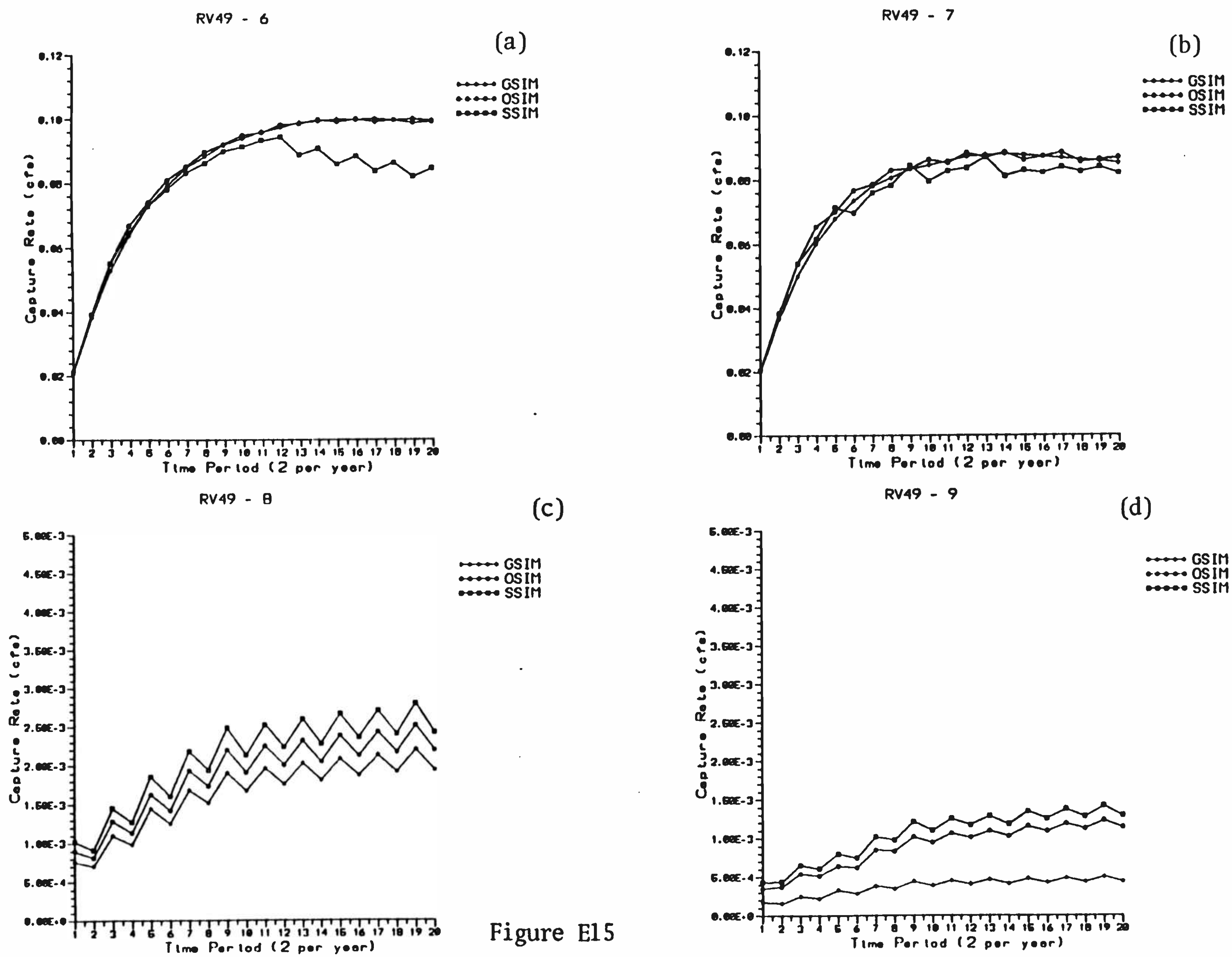

RV49 - 6
(a)
GSIM
OSIM
SSIM
RV49 - 7
(b)
GSIM
OSIM
SSIM
RV49 - 8
(c)
GSIM
OSIM
SSIM
RV49 - 9
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E15

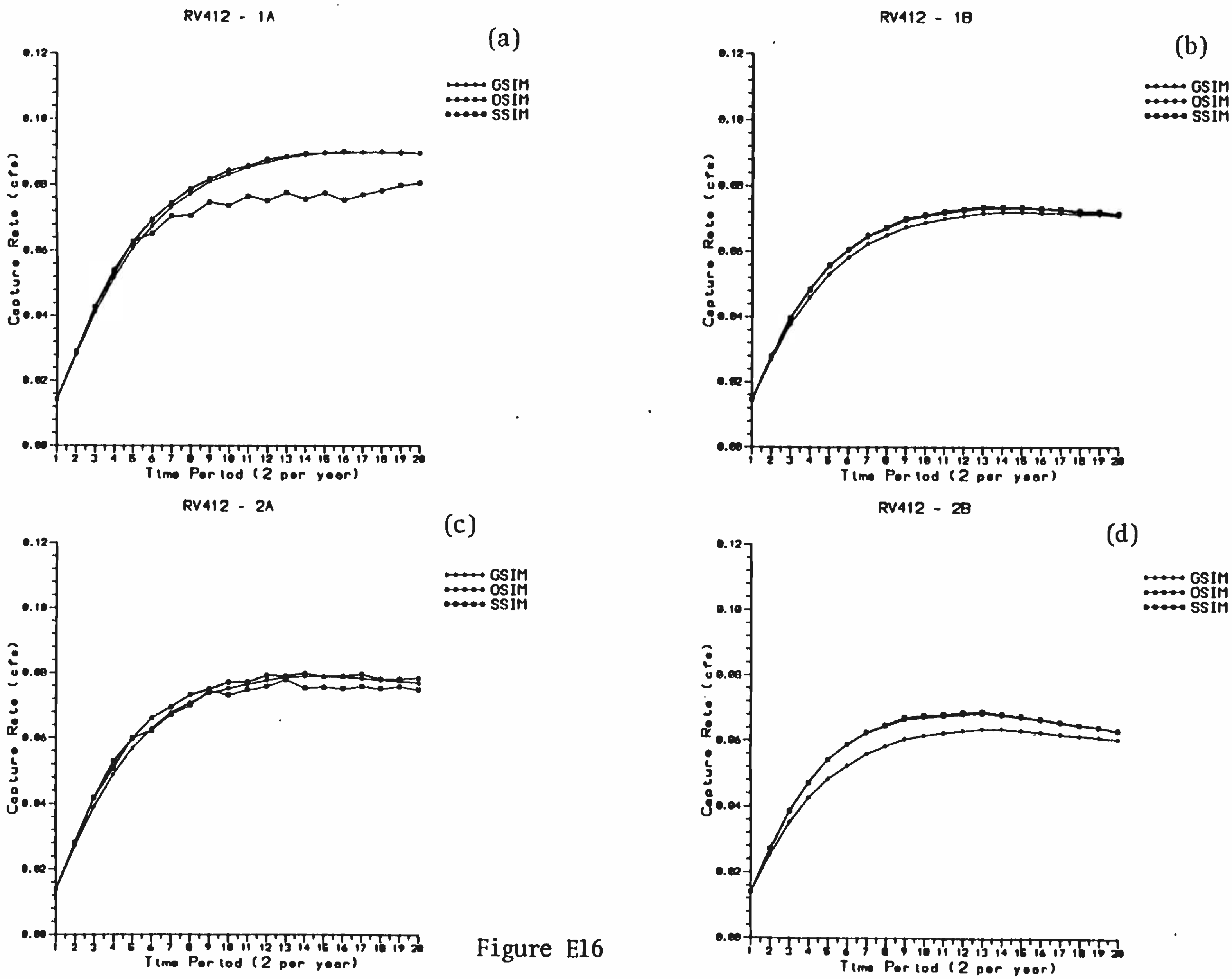

RV412 - 1A
(a)
RV412 - 1B
(b)
RV412 - 2A
(c)
RV412 - 2B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)

Figure E16

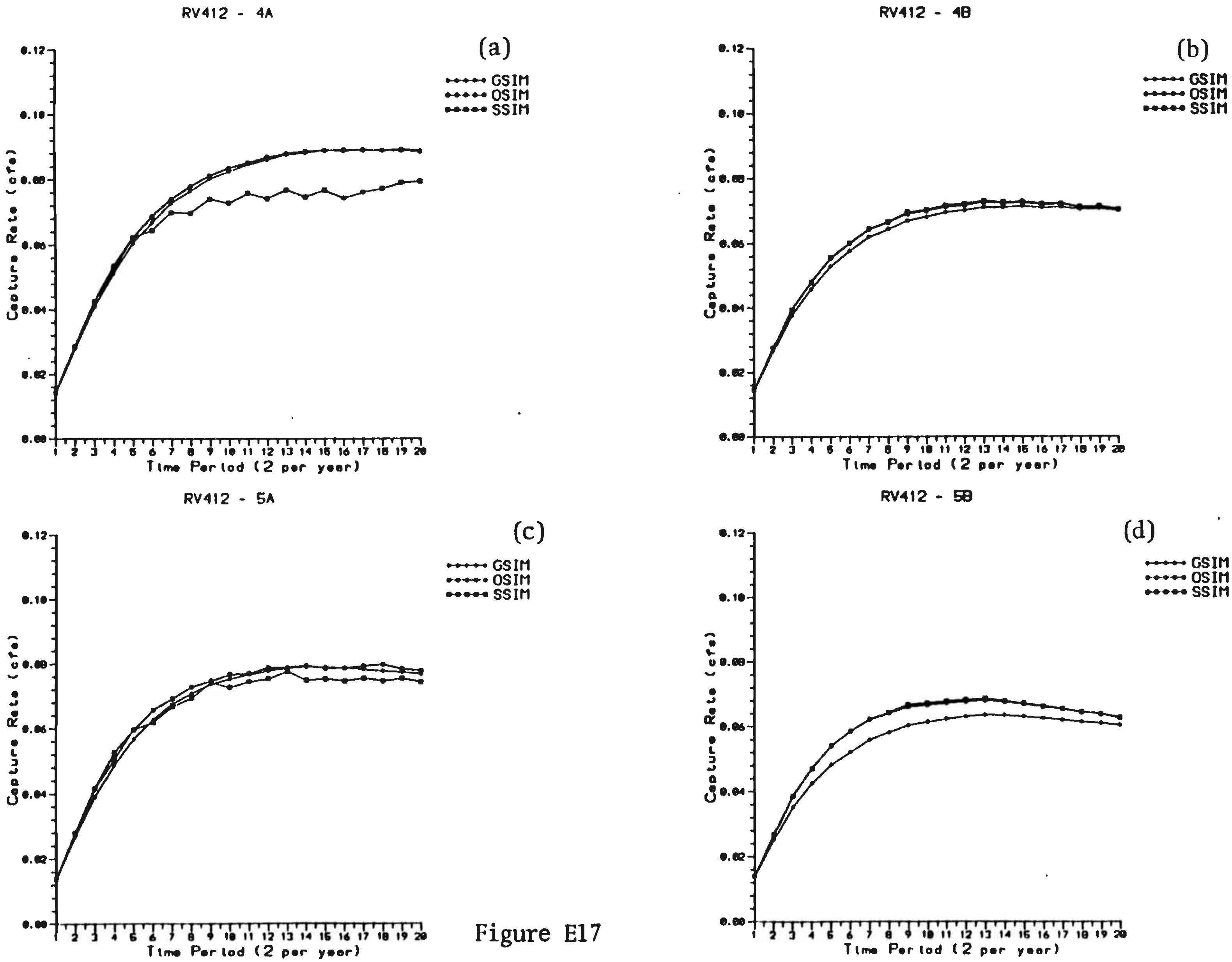
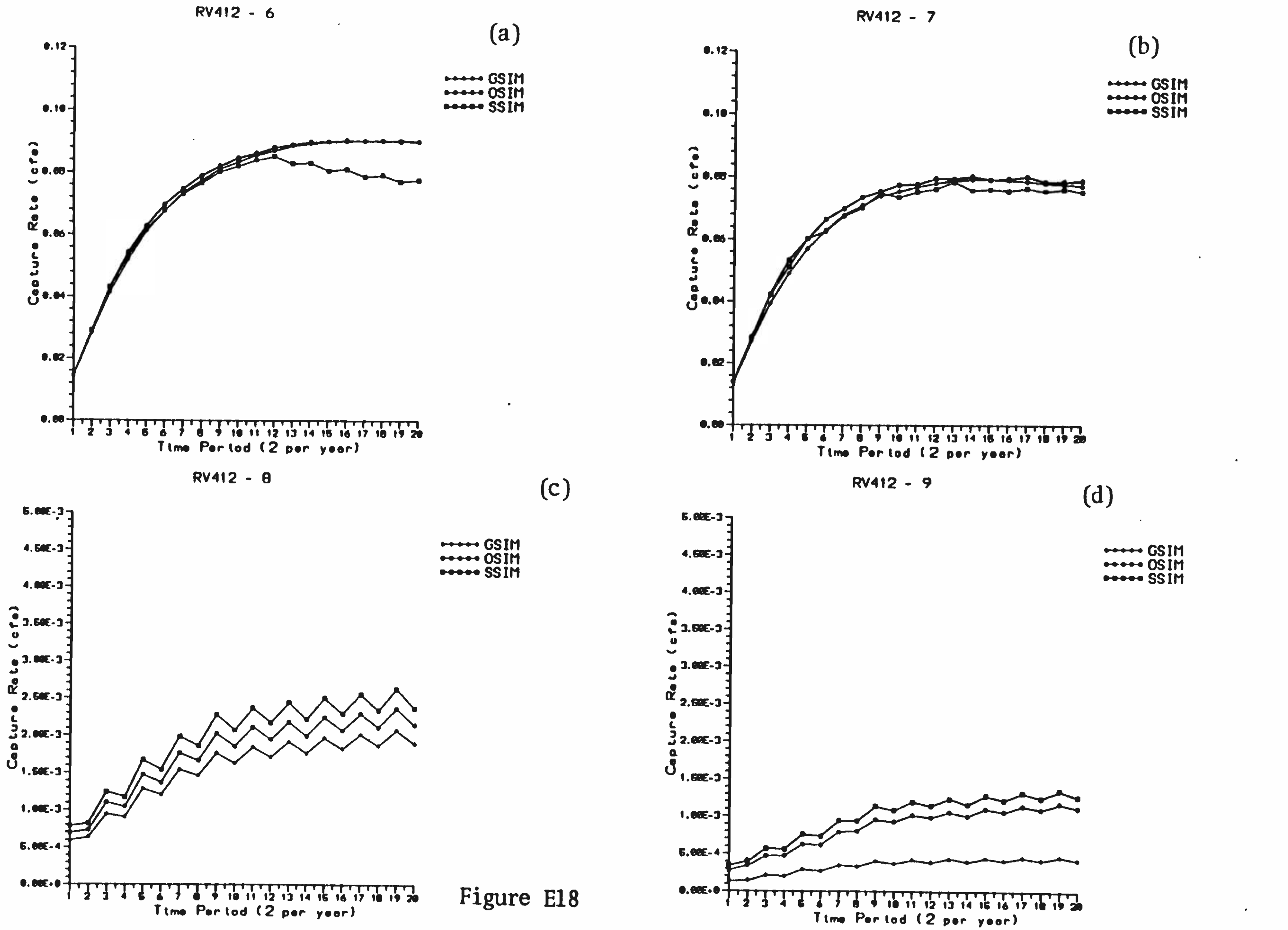

RV412 - 4A
(a)
RV412 - 4B
(b)
RV412 - 5A
(c)
RV412 - 5B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E17



RV412 - 6
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV412 - 7
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV412 - 8
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV412 - 9
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E18

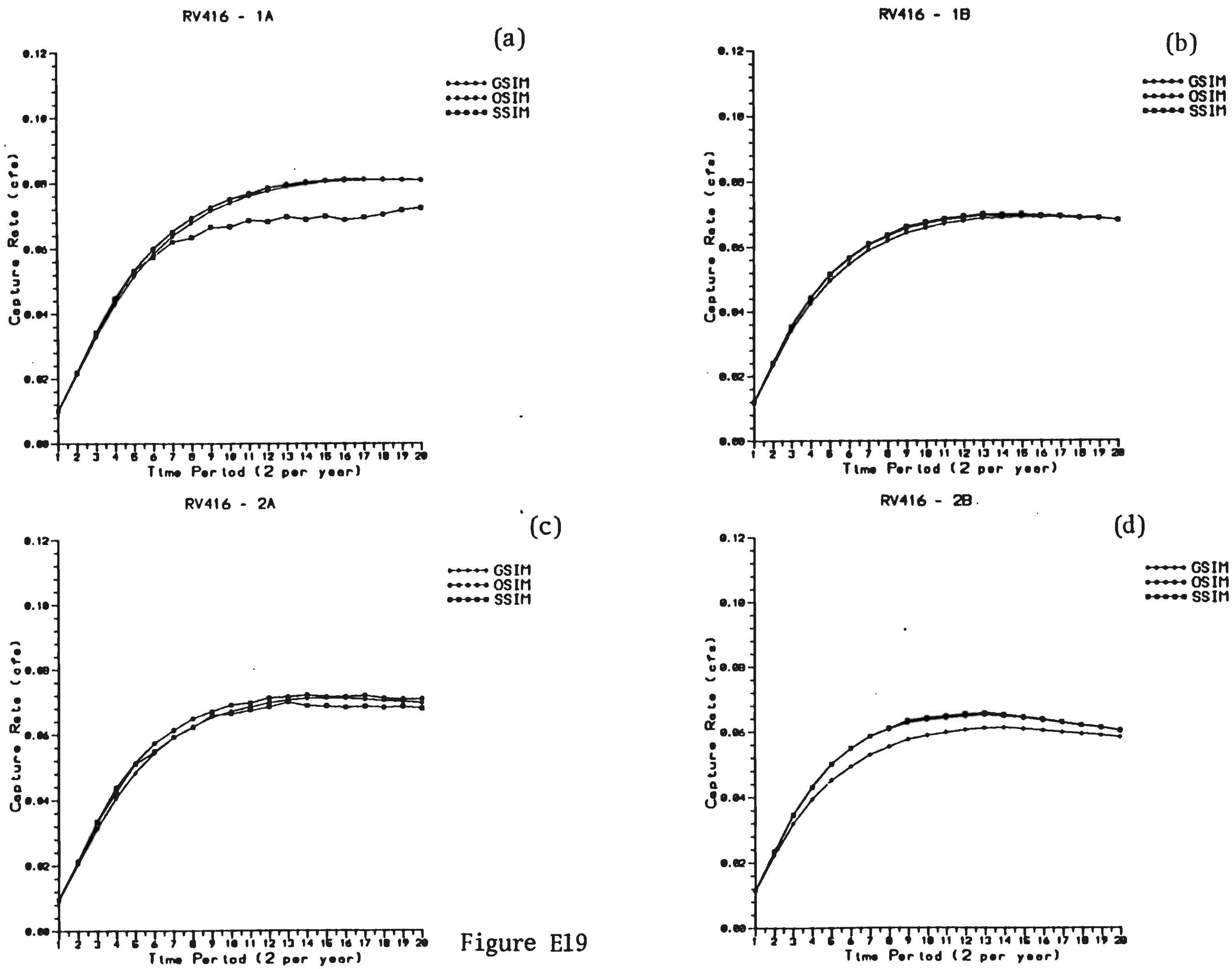

RV416 - 1A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time Period (2 per year)
RV416 - 1B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV416 - 2A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV416 - 2B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E19

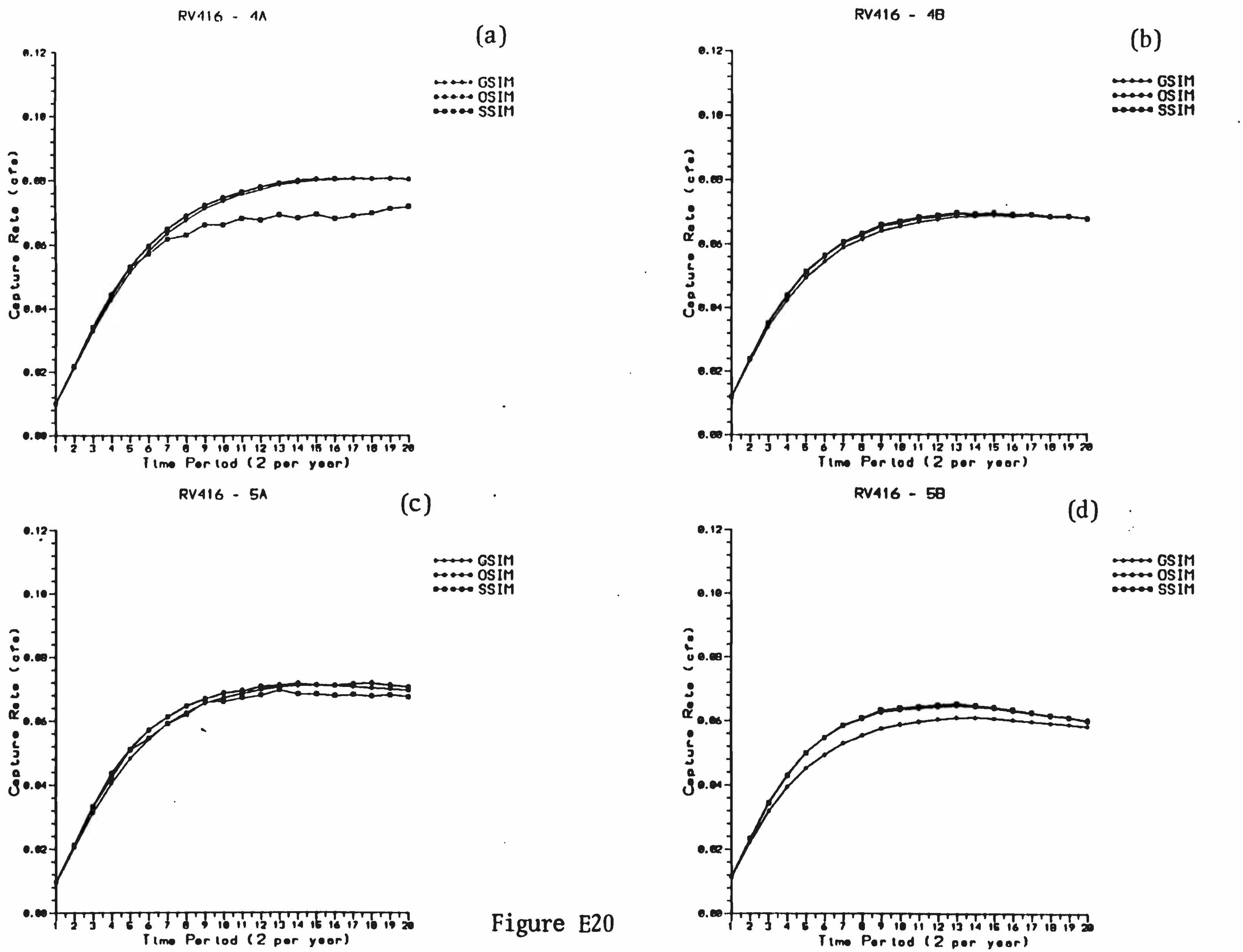

RV416 - 4A
(a)
RV416 - 4B
(b)
RV416 - 5A
(c)
RV416 - 5B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure E20

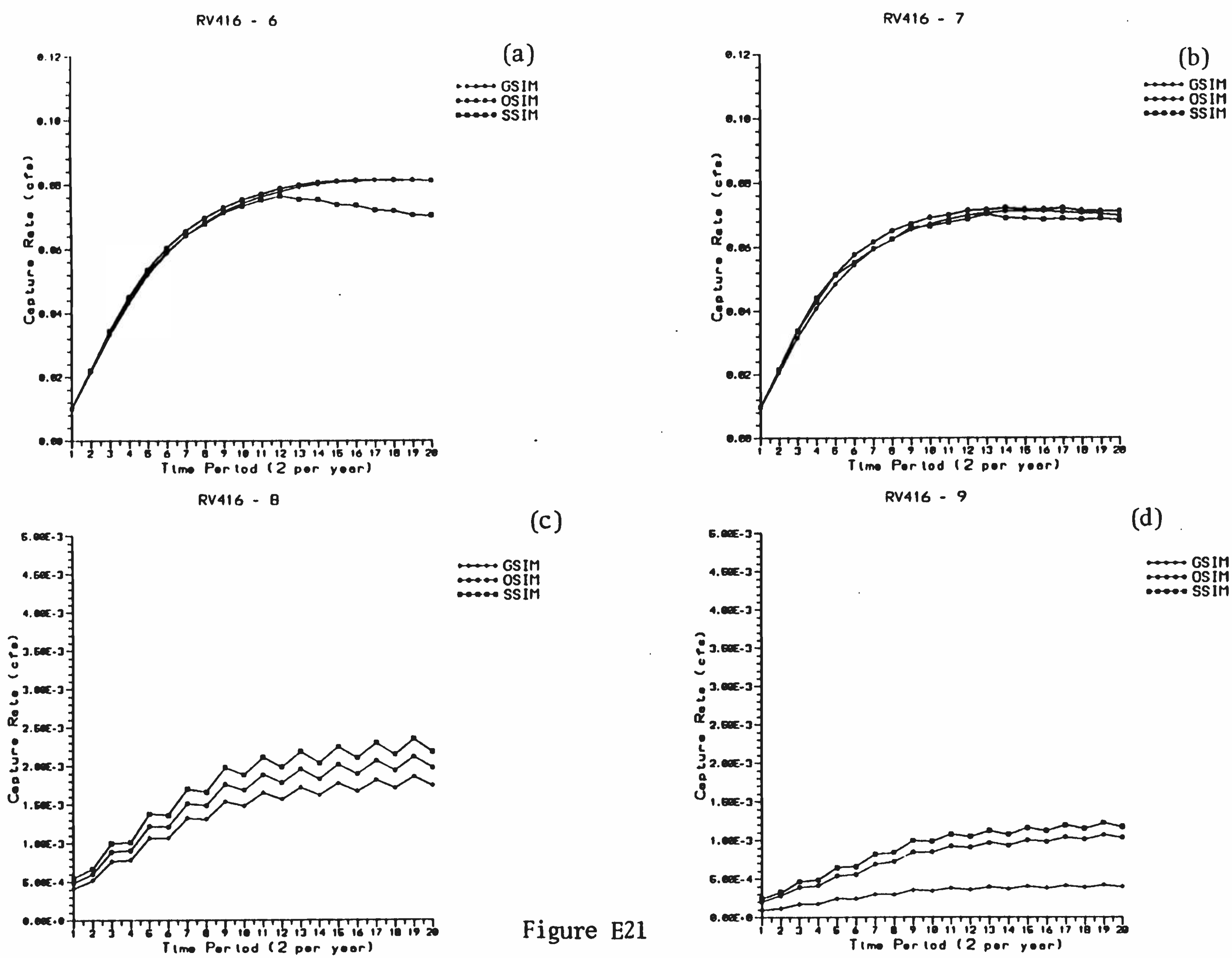

RV416 - 6
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV416 - 7
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV416 - 8
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV416 - 9
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E21

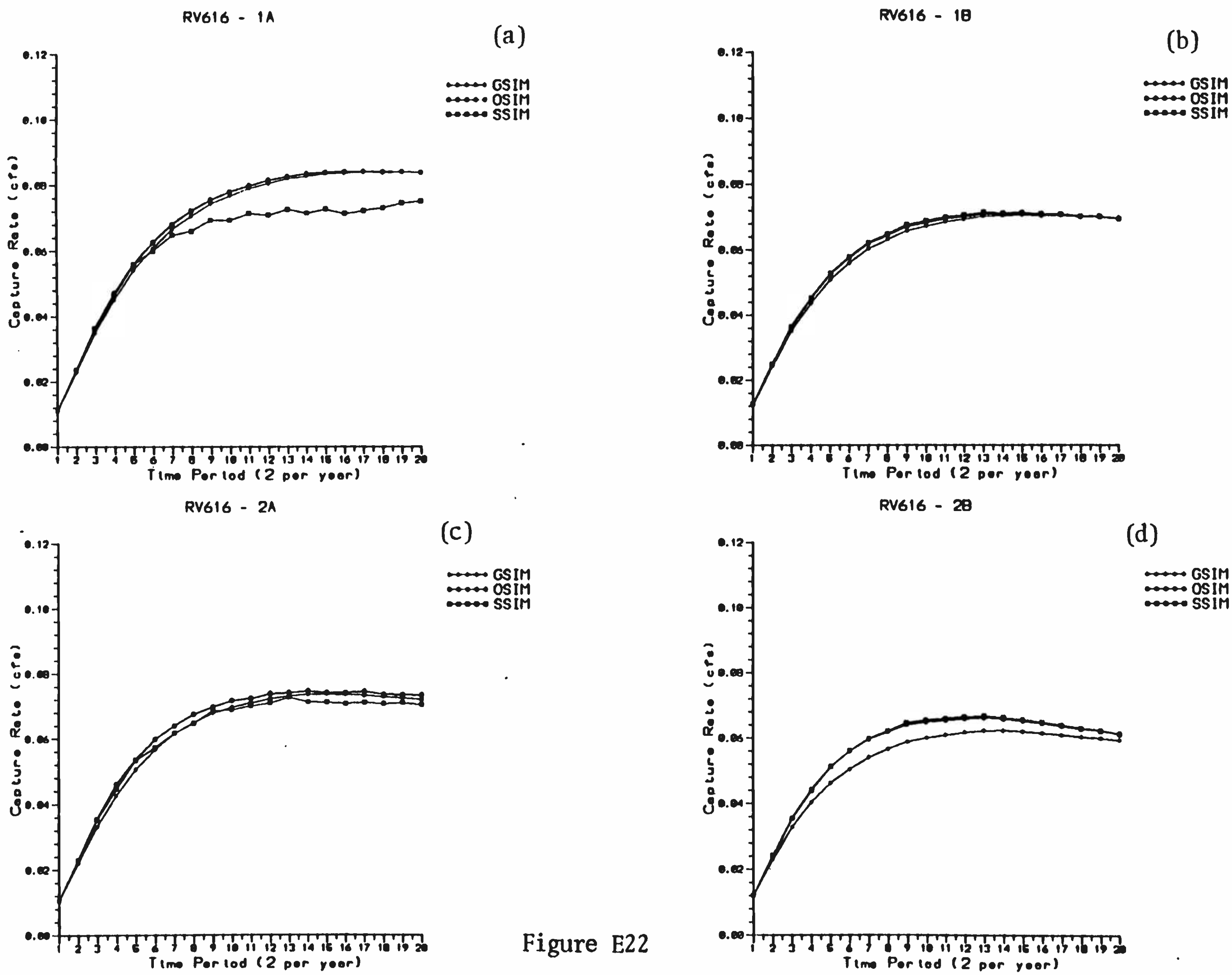
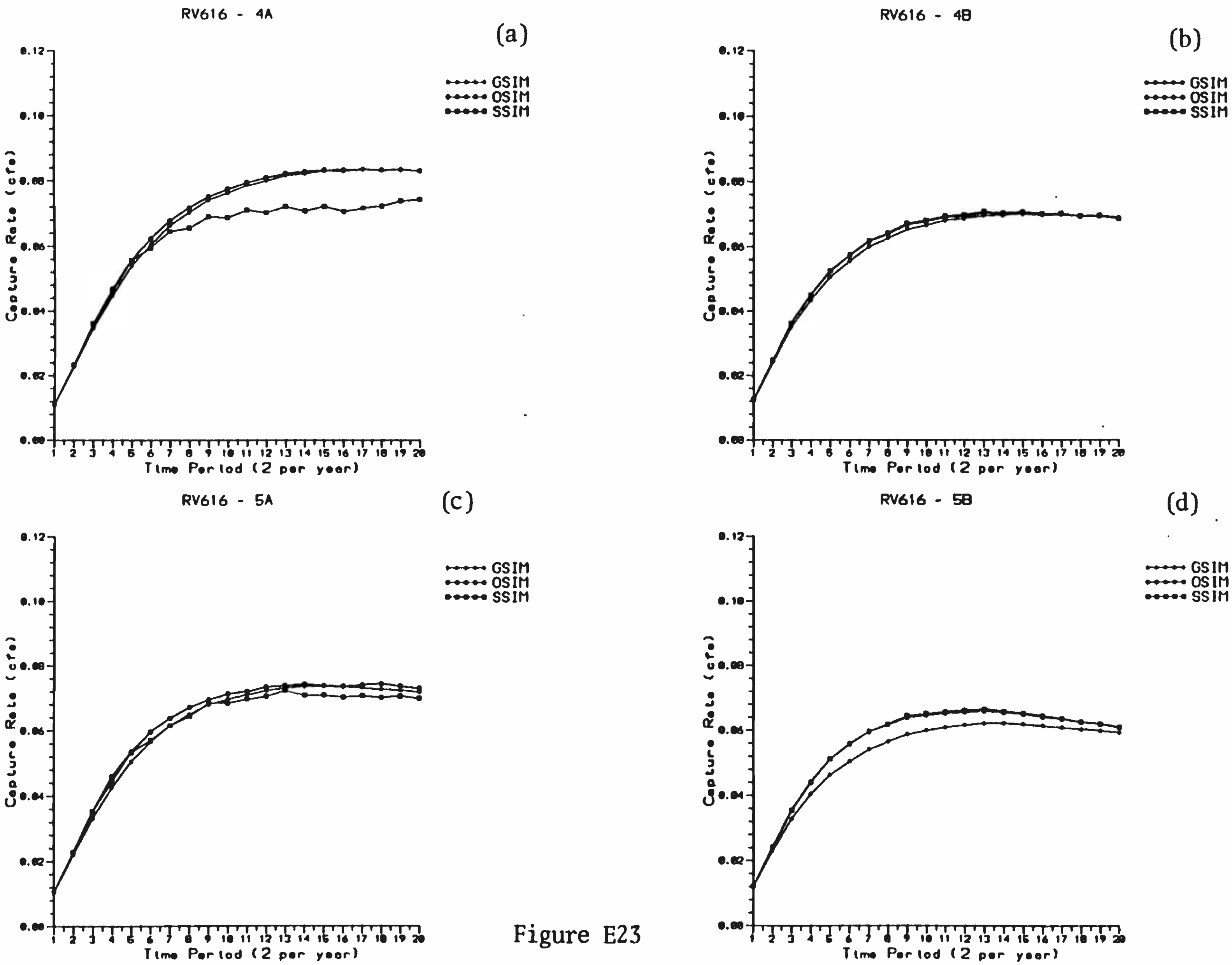

RV616 - 1A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV616 - 1B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV616 - 2A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV616 - 2B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E22



RV616 - 4A
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV616 - 4B
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV616 - 5A
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV616 - 5B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E23

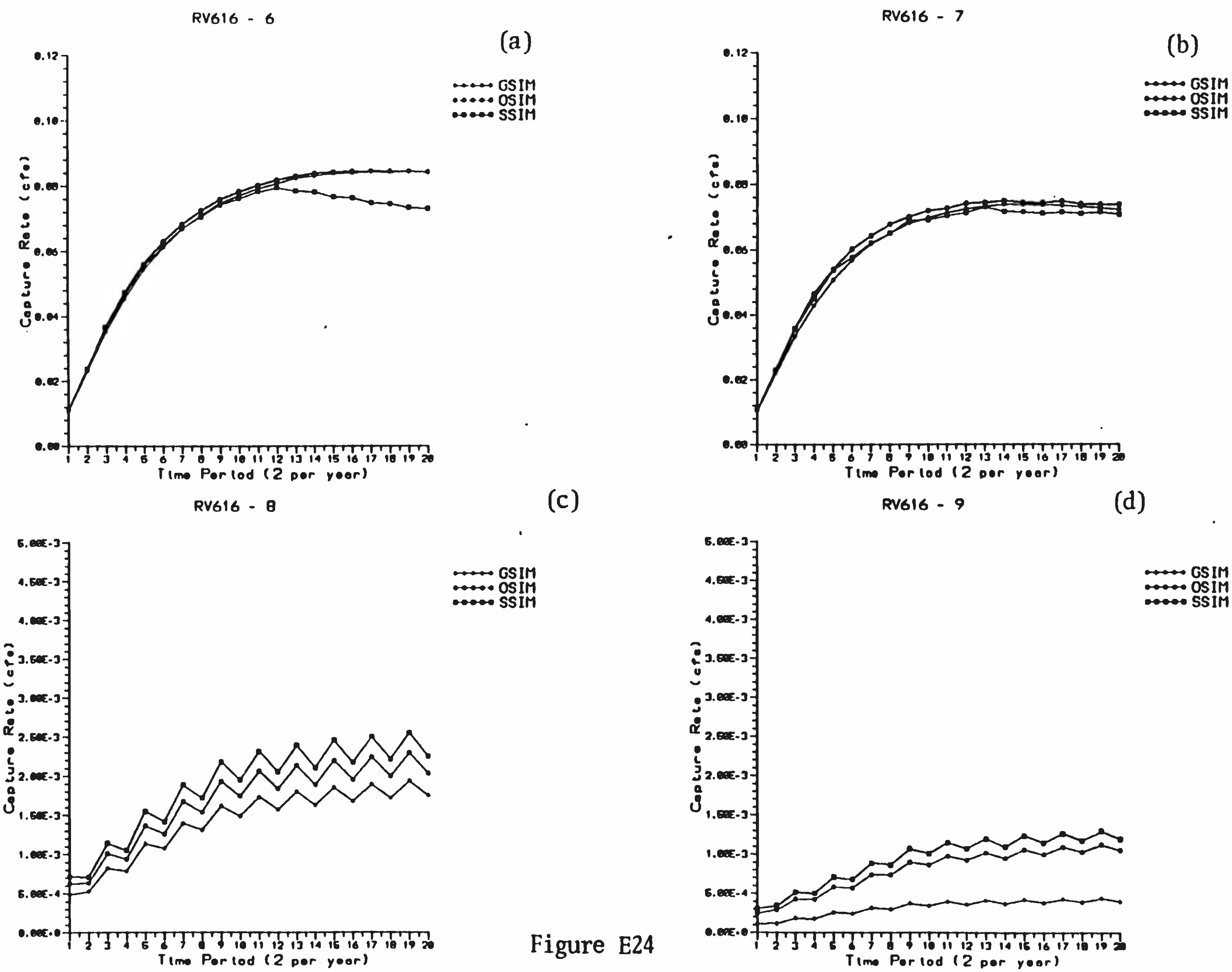

RV616 - 6
(a)
Capture Rate (cfs)
Time Period (2 per year)
GSIM
OSIM
SSIM
RV616 - 7
(b)
Capture Rate (cfs)
Time Period (2 per year)
GSIM
OSIM
SSIM
RV616 - 8
(c)
Capture Rate (cfs)
Time Period (2 per year)
GSIM
OSIM
SSIM
RV616 - 9
(d)
Capture Rate (cfs)
Time Period (2 per year)
GSIM
OSIM
SSIM

Figure E24

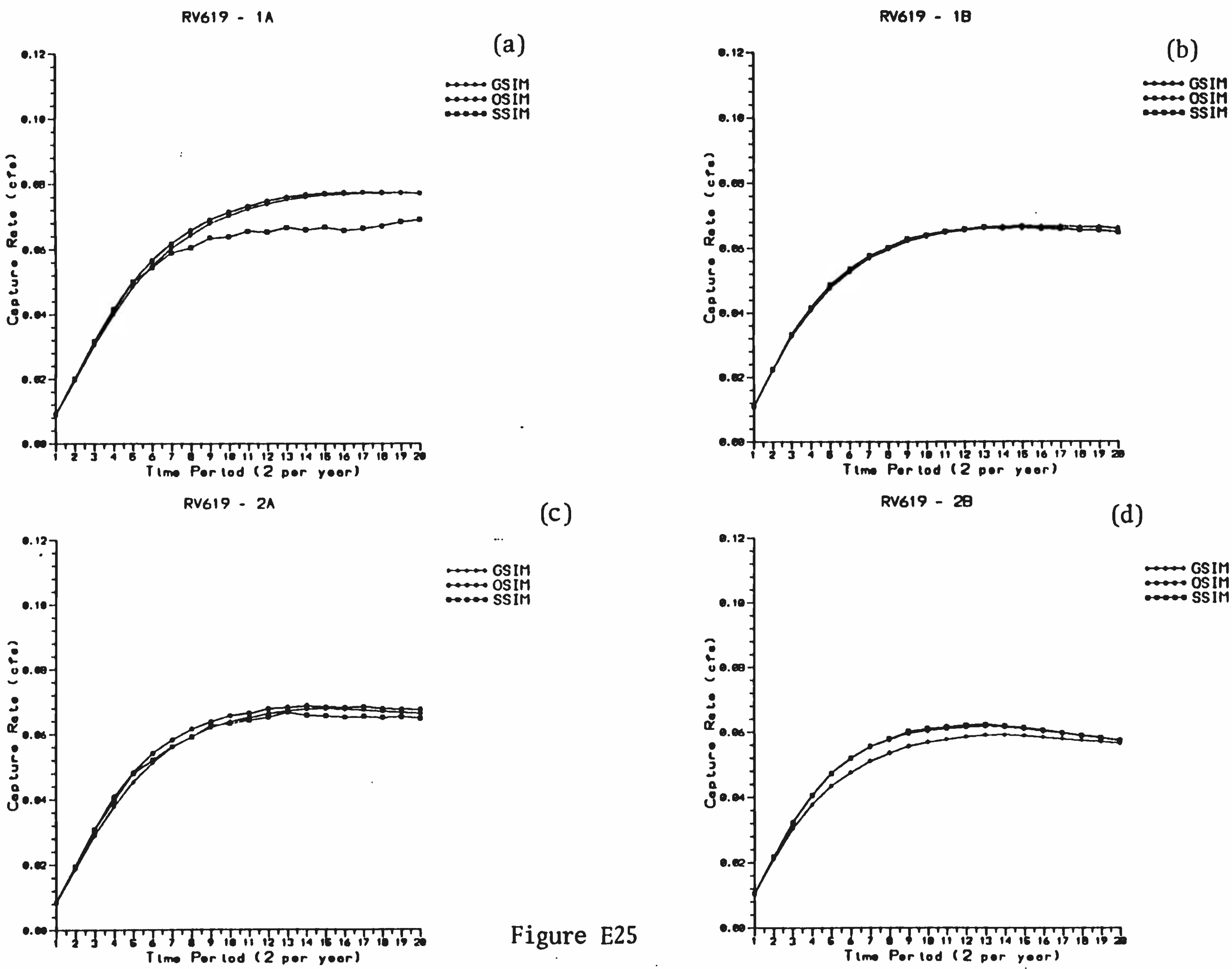

RV619 - 1A
(a)
RV619 - 1B
(b)
RV619 - 2A
(c)
RV619 - 2B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure E25

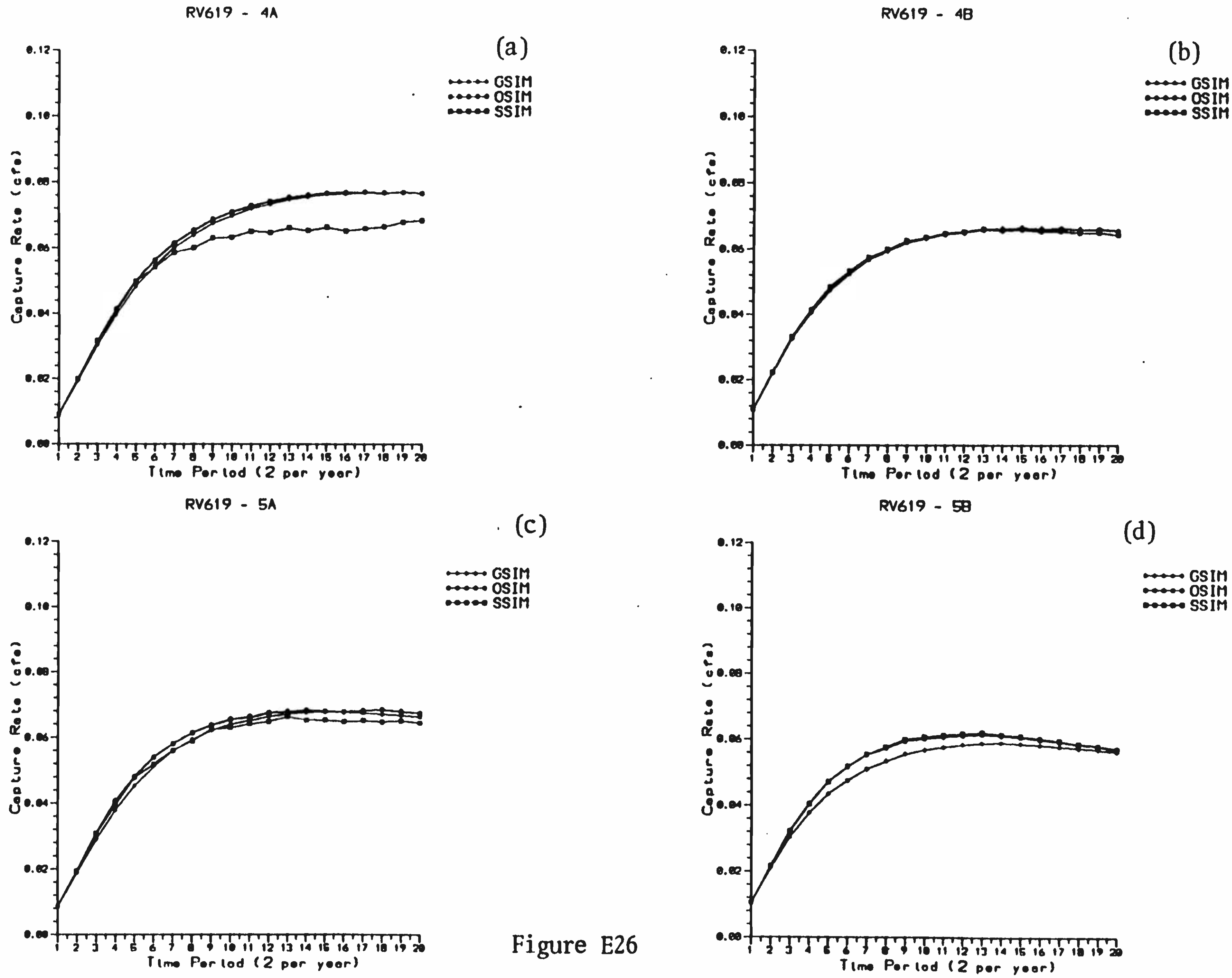

RV619 - 4A
(a)
RV619 - 4B
(b)
RV619 - 5A
(c)
RV619 - 5B
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure E26

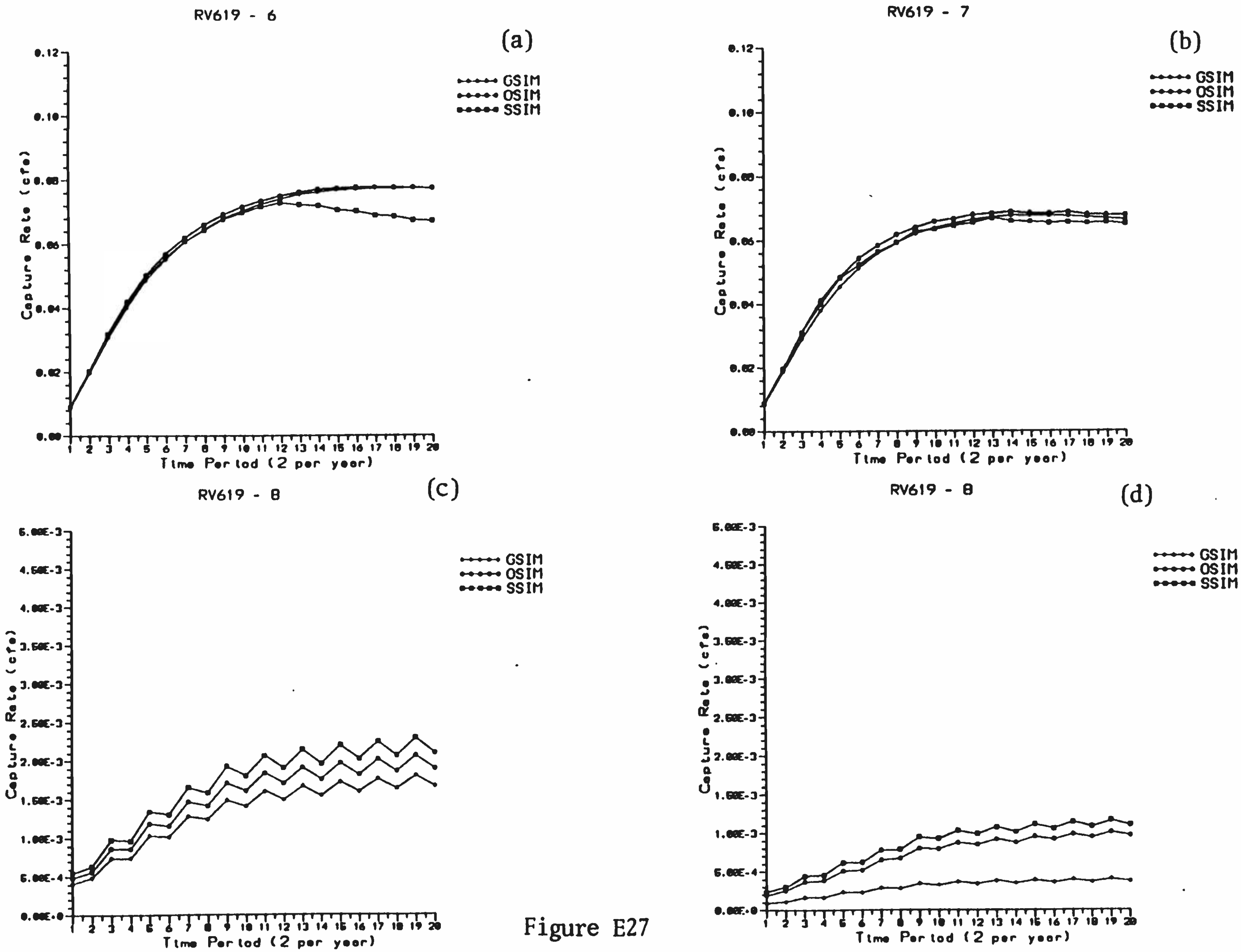

RV619 - 6
(a)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV619 - 7
(b)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV619 - 8
(c)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)
RV619 - 8
(d)
GSIM
OSIM
SSIM
Capture Rate (cfs)
Time Period (2 per year)

Figure E27

APPENDIX F

Injection Rate Plots

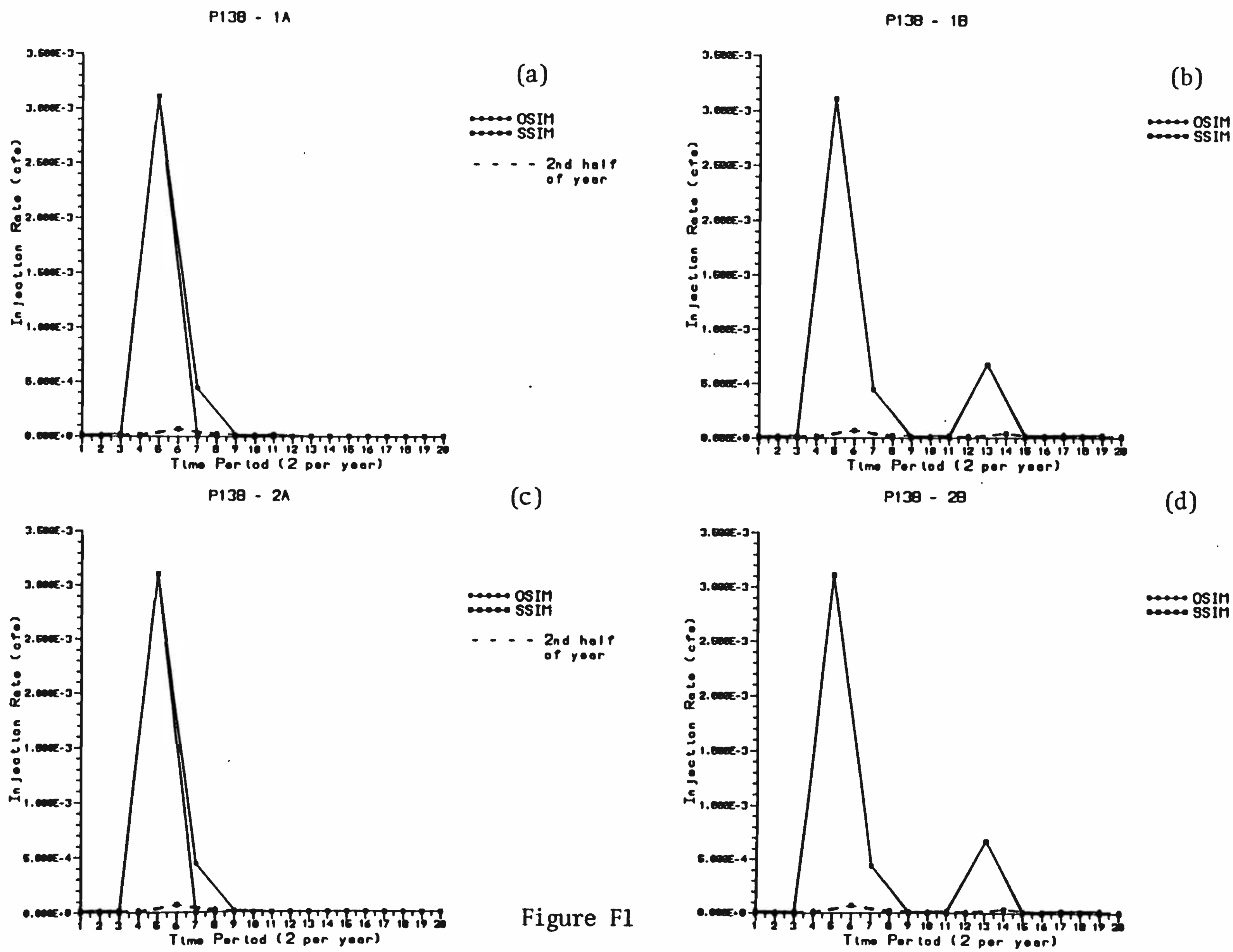

P138 - 1A
(a)
OSIM
SSIM
2nd half of year
Injection Rate (cfs)
Time Period (2 per year)
P138 - 1B
(b)
P138 - 2A
(c)
P138 - 2B
(d)
3.500E-3
3.000E-3
2.500E-3
2.000E-3
1.500E-3
1.000E-3
5.000E-4
0.000E+0

Figure F1

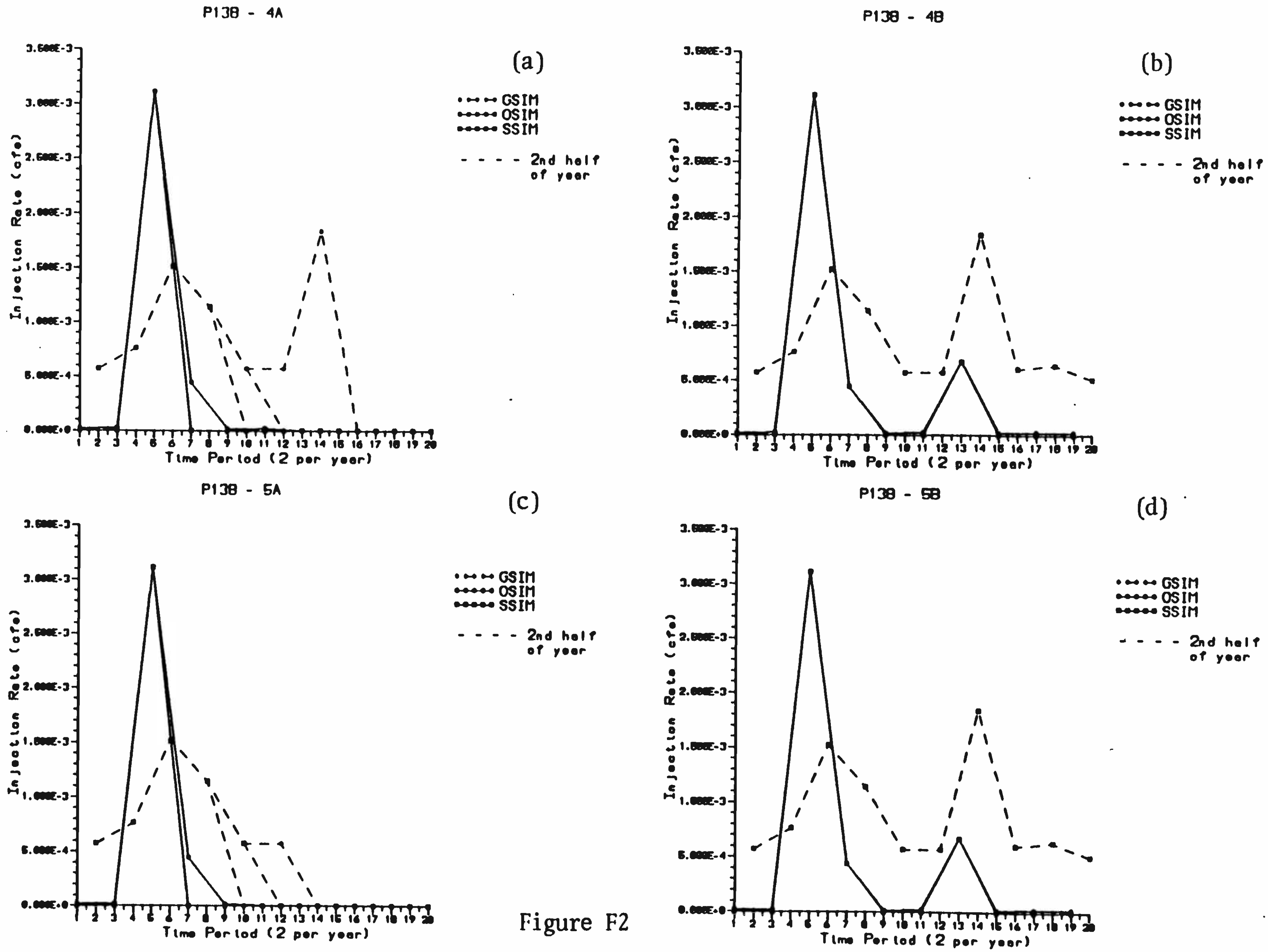

P13B - 4A
(a)
P13B - 4B
(b)
P13B - 5A
(c)
P13B - 5B
(d)
Injection Rate (cfs)
Time Period (2 per year)
GSIM
OSIM
SSIM
2nd half of year

Figure F2

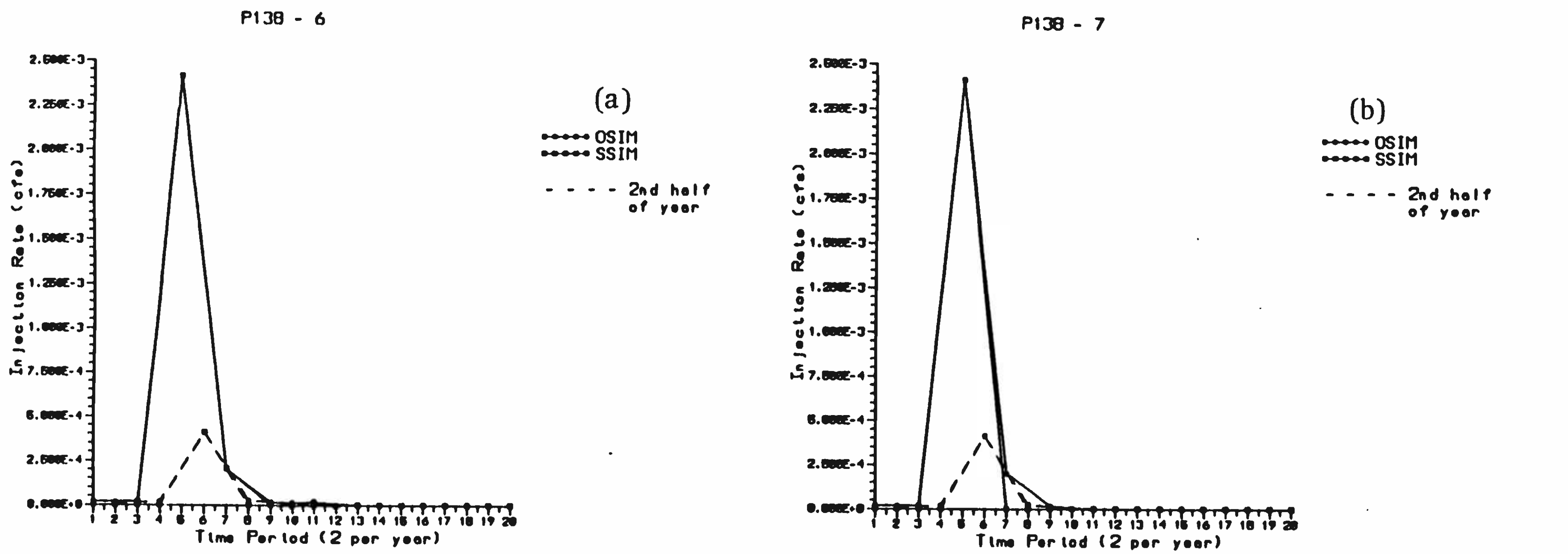

P138 - 6
(a)
OSIM
SSIM
2nd half of year
Injection Rate (cfs)
Time Period (2 per year)
P138 - 7
(b)
OSIM
SSIM
2nd half of year
Injection Rate (cfs)
Time Period (2 per year)

Figure F3

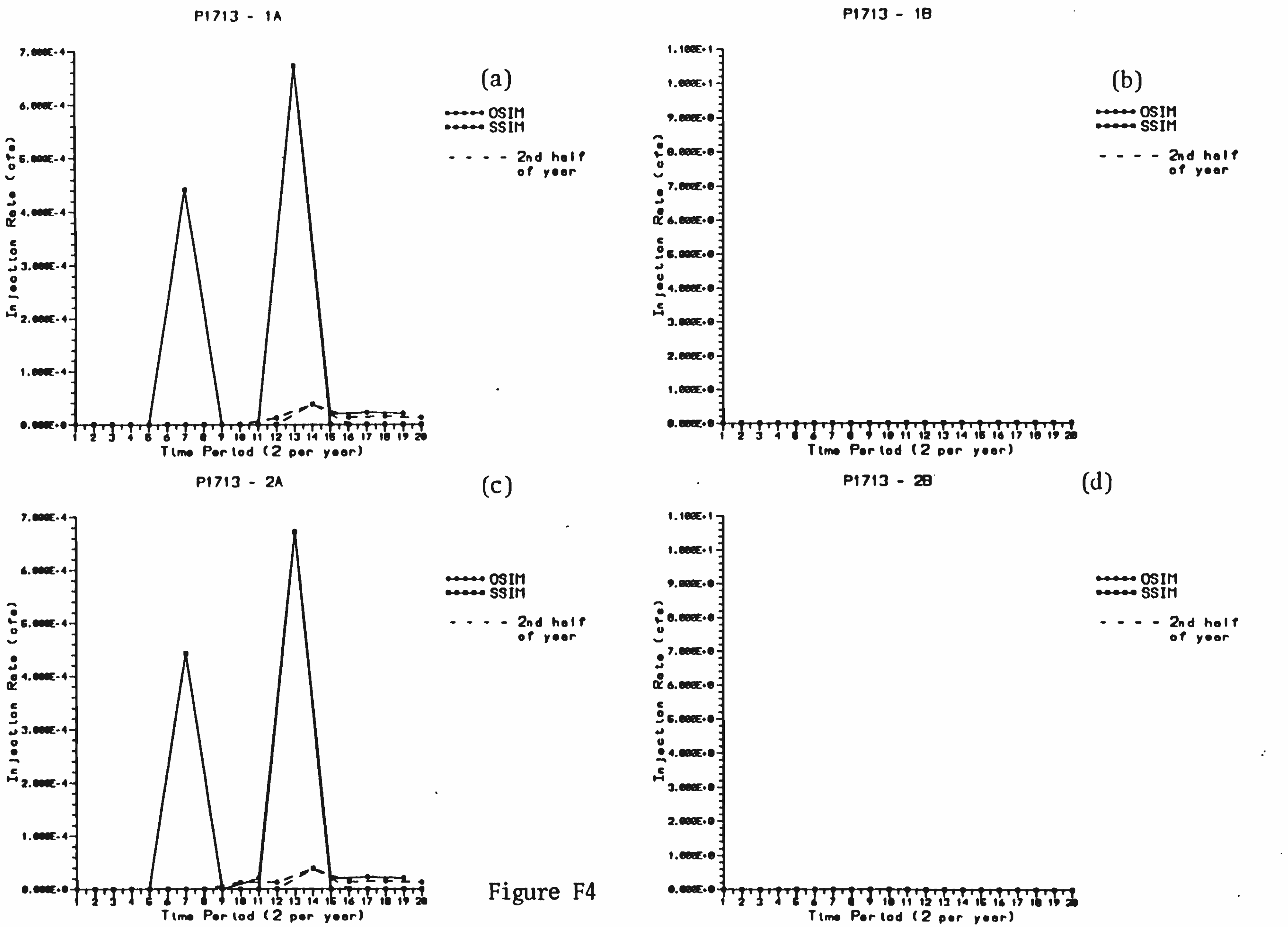
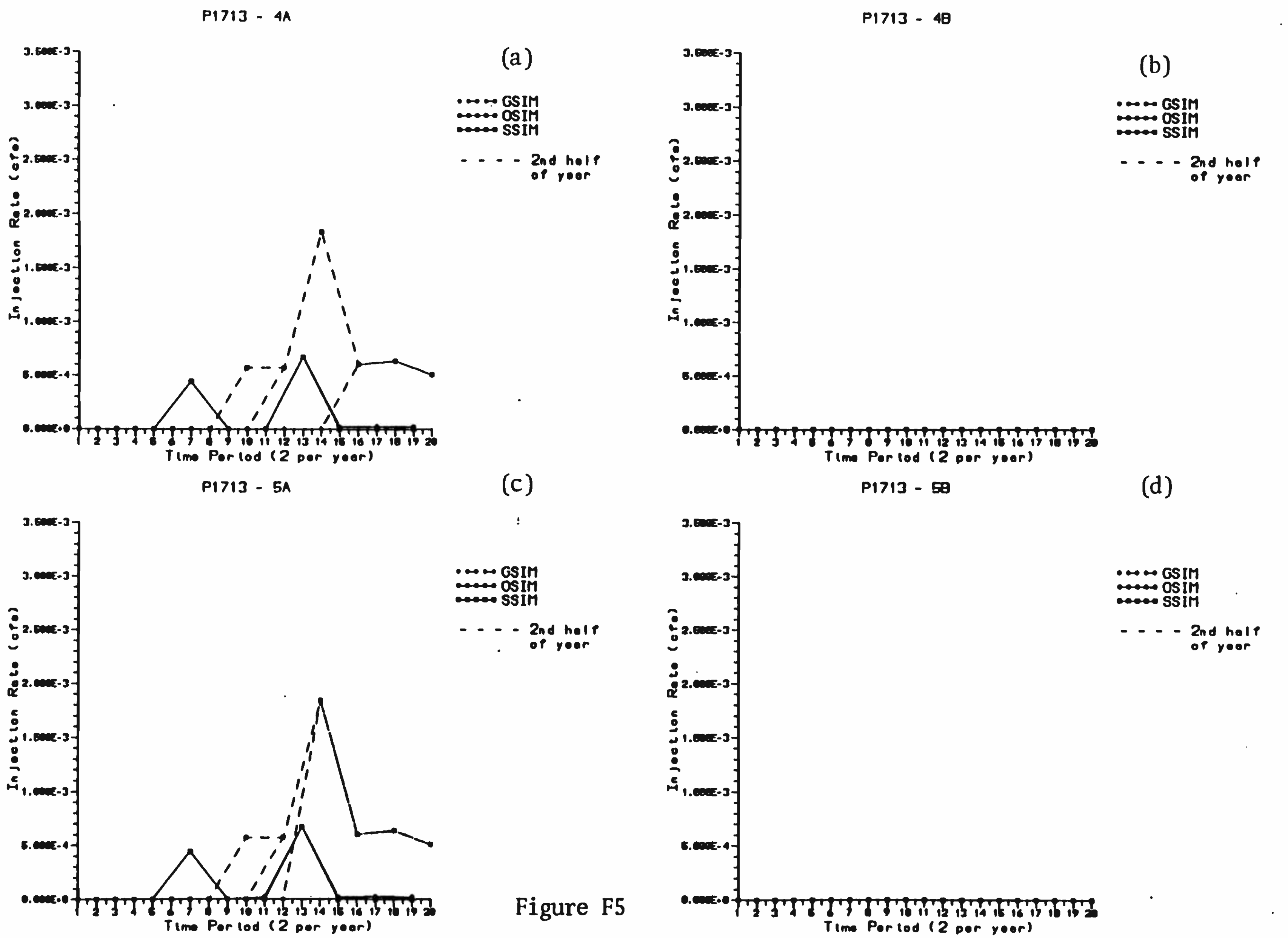

P1713 - 1A
(a)
OSIM
SSIM
2nd half of year
Injection Rate (cfs)
Time Period (2 per year)
P1713 - 1B
(b)
OSIM
SSIM
2nd half of year
Injection Rate (cfs)
Time Period (2 per year)
P1713 - 2A
(c)
OSIM
SSIM
2nd half of year
Injection Rate (cfs)
Time Period (2 per year)
P1713 - 2B
(d)
OSIM
SSIM
2nd half of year
Injection Rate (cfs)
Time Period (2 per year)

Figure F4



P1713 - 4A
(a)
GSIM
OSIM
SSIM
2nd half of year
Injection Rate (afe)
Time Period (2 per year)
P1713 - 4B
(b)
P1713 - 5A
(c)
P1713 - 5B
(d)

Figure F5

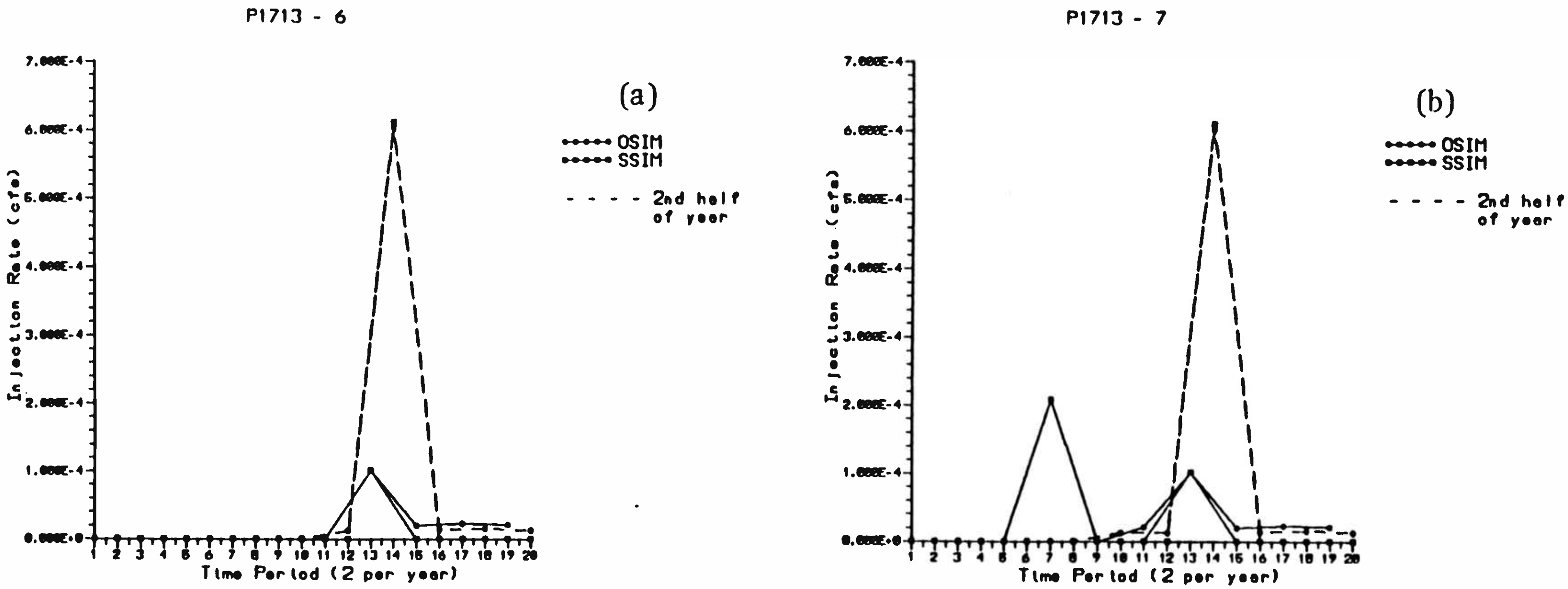

P1713 - 6
(a)
7.000E-4
6.000E-4
5.000E-4
4.000E-4
3.000E-4
2.000E-4
1.000E-4
0.000E+0
Injection Rate (cfs)
Time Period (2 per year)
OSIM
SSIM
2nd half of year
P1713 - 7
(b)
7.000E-4
6.000E-4
5.000E-4
4.000E-4
3.000E-4
2.000E-4
1.000E-4
0.000E+0
Injection Rate (cfs)
Time Period (2 per year)
OSIM
SSIM
2nd half of year

Figure F6